Environmental considerations
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FOREWORD

This document provides technical information previously contained in the Fourth Edition of the Health and Safety Executive’s ‘Offshore Installations: Guidance on Design, Construction and Certification’ (1990 edition plus amendments)\(^{(1)}\). The ‘Guidance’ was originally published in support of the certification regime under SI289, the Offshore Installations (Construction and Survey) Regulations 1974\(^{(2)}\). However, SI289 was revoked by the Offshore Installations (Design and Construction, etc) Regulations, 1996, which also introduced the verification provisions into the Offshore Installations (Safety Case) Regulations, 1992. The ‘Guidance’ was formally withdrawn in its entirety on 30 June 1998 (see HSE OSD Operations Notice 27\(^{(3)}\)).

The withdrawal of the ‘Guidance’ was not a reflection of the soundness (or otherwise) of the technical information it contained; some sections (or part of sections) of the ‘Guidance’ are currently referred to by the offshore industry. For this reason, after consultation with industry, relevant sections are now published as separate documents in the HSE Offshore Technology (OT) Report series.

It should be noted that the technical content of the ‘Guidance’ has not been updated as part of the reformatting for OTO publication, although prescriptive requirements and reference to the former regulatory regime have been removed. **The user of this document must therefore assess the appropriateness and currency of the technical information for any specific application. Additionally, the user should be aware that published sections may cease to be applicable in time and should check with Operations Notice 27, which can be viewed at [http://www.hse.gov.uk/hid/osd/notices/on_index.htm](http://www.hse.gov.uk/hid/osd/notices/on_index.htm), for their current status.**
1. INTRODUCTION AND SCOPE

1.1 SOURCE OF INFORMATION

This Offshore Technology (OT) Report provides technical information on metocean parameters for Offshore Installations in UK waters. It is based on guidance previously contained in Section 11 of the Fourth Edition of the Health and Safety Executive’s ‘Offshore Installations: Guidance on Design, Construction and Certification’\(^{(1)}\) which was withdrawn in 1998. As discussed in the Foreword, whilst the text has been reformatted for Offshore Technology publication, the technical content has not been updated. The appropriateness and currency of the information contained in this document must therefore be assessed by the user for any specific application.

The information on environmental conditions presented in this document is supported by two background reports, OTH 89 299\(^{(4)}\) and OTH 89 300\(^{(5)}\).

1.2 CONSIDERATIONS

An accurate assessment of the meteorological and oceanographic environment is fundamental to the sound design of offshore installations. Only on this basis is it possible to calculate the loads likely to be imposed by natural phenomena and to predict the behaviour of structures under extreme loading conditions and prolonged exposure. Environmental forces are relatively more important in the design of offshore structures than with many other types of engineering structures.

Metocean design parameters need to be established in the following areas:

- the speed and direction of winds and the effect of averaging period and height above the surface of the sea on their characteristics
- the heights, periods and directions of waves, the probability of their occurrence and the effect of currents, sea bed topography and other factors likely to modify their characteristics
- the water depth and variations in water level from tide and storm surge
- the speed and direction of tidal and other currents
- air and sea temperatures
- the extent of snow and ice accumulations
- the extent to which marine growth may form on the submerged sections of the installation.

The metocean parameters described in this document are relevant to the design of fixed, floating and compliant installations, but not necessarily to their tow-out to location, which will be the subject of special criteria developed for the particular operation.

1.3 RETURN PERIODS OF PARAMETER VALUES

Most metocean phenomena vary with time in a random manner, and extreme values to be used in design can only be chosen on a probabilistic basis. The probability that a metocean parameter will exceed a given value
leads to the concept of a ‘return period’ (which is discussed in detail in OTH 89 299 and OTH 89 300). The definition of return period adopted for this report is:

The return period of a stated value of a metocean variable is the average period of time between exceedances of that value.

The value with an N-year return period is commonly called ‘the N-year return value’ of the variable. Extreme values given in this document are generally based on the 50-year return value, although formulae are given which enable extreme values with other return periods to be calculated. These values may be relevant to the determination of suitable combinations of individual metocean parameters, as discussed in Section 10.

For mobile installations that are not on location throughout the year, it may be appropriate to establish 50-year return values of metocean parameters for the season of operation alone.

It should be noted that where a structure or part of a structure is likely to respond dynamically to the forces on it, or for geometric reasons, metocean parameters with return periods shorter than 50 years may produce the extreme response from the structure.

In determining the structural performance under operating conditions of those parts of a compliant installation which are subject to wave loading, the maximum operating condition should be determined using environmental parameters which are not less than those likely to be exceeded, on average, once a month (i.e. conditions exceeded 12 times a year).

The fatigue performance of an installation is a function of the whole range of metocean variables, not just their extreme values.

1.4 SITE-SPECIFIC AND INDICATIVE DESIGN PARAMETERS

In general, the metocean climate varies from location to location. The most accurate design parameters are therefore derived from long data sets gathered at the intended location of an installation, i.e. site-specific data. However, data sets of sufficient length, accuracy and completeness are not always available and design must then be based on more general, or indicative, values.

Sections 3 to 9 describe the preferred quantity and quality of data to be collected at a location to establish site-specific metocean design parameters. If site-specific data sets are available for periods less than those recommended, careful consideration should be given to the validity of any criteria established from them, giving due weight to the indicative values provided.

Sections 3 to 9 contain maps and tables of indicative values of extreme individual metocean parameters (usually with return periods of 50 years). The maps cover UK designated waters up to 15°W and extend into adjoining areas where the data are readily available. The methods used to establish the indicative values are also outlined.

The indicative values are estimates which were generated on the basis of the reliable long-term data sets that were available at the time of preparing the Fourth Edition Guidance, supplemented by mathematical modelling techniques. For each parameter, the indicative values have been derived from the relevant data set using one analysis technique consistently over the whole geographical area. No explicit safety factors
have been included in the values but implicit interpretations have been made, for example in extreme value extrapolations, to reduce the risk that the values might be underestimates.

1.5 FURTHER INFORMATION

This document should be read in association with other OT Reports dealing with hydrostatic and hydrodynamic loads (OTO 2001 013) and site investigations (OTO 2001 012).

1.6 DEFINITIONS

Note: Italic words are cross references to other definitions in the list.

**Average spring tidal current:** See tides.

**Chart datum, CD:** The datum adopted by the Admiralty for tidal predictions and depth soundings as plotted on navigation charts. Since 1975, Chart Datum has been defined as lowest astronomical tide; on earlier Admiralty charts, a different definition applied. Chart Datum varies from chart to chart. (This document uses mean sea level as the datum for sea level variations.)

**Circulation:** See residual currents.

**Cumulative frequency distribution:** See wave exceedance diagram.

**Current:** Unless otherwise specified, a flow of water past a fixed location - more precisely described as an Eulerian current. (A Lagrangian current is measured by following the movement of a water particle.) Currents are usually described with a current speed and direction; measurements are usually analysed in terms of the tidal current and residual currents.

**Current ellipse:** See tides - tidal current.

**Current speed:** Unless otherwise indicated, taken to be the horizontal speed of the current (independent of direction). The speed varies throughout the water column.

Depth-averaged current speed is the speed of the current averaged throughout the water column.

**Datum:** In this document the datum for measuring changes in still water level is the local mean sea level. See also Chart Datum.

**Depth-averaged current speed:** See current speed.

**Design value:** In the design of offshore installations, the extreme value of a metocean variable whose exceedance has a return period that satisfies the design specification.

**Design wave:** Extreme amplitude design wave is the periodic wave having the same height as the extreme wave with the return period required by the specification. Used as the initial design condition for a non-compliant offshore structure. It may have a range of wave periods associated with it and its expected direction may be specified.
Extreme response design wave or waves may be smaller than the extreme amplitude design wave but produce a greater loading on the structure.

**Extreme value**: An estimate of the value of a metocean variable with a stated *return period*.

**Highest astronomical tide, HAT**: The highest *tidal level* the undisturbed *tide* will ever reach above a *datum*. Usually obtained from measurements or predictions covering several decades where these are available. Alternatively, it can be estimated from predictions covering a period when the astronomical positions of the moon and sun are known to be favourable in producing high tidal ranges. See also *lowest astronomical tide*, LAT.

**Indicative values (of a metocean parameter)**: Values of a metocean parameter to be used when reliable values based on *site-specific measurements* or other studies are not available. In this report they are generally presented as contours on maps; the contours are based on those reliable long-term data sets that are available, supplemented by mathematical modelling techniques. They do not take account of small-scale local features.

**Joint probability**: When two or more metocean variables interact in producing forces on a structure, it may be necessary to determine the probabilities with which various combinations of them occur, i.e. their joint probability of occurrence.

**Lowest astronomical tide, LAT**: The lowest *tidal level* the undisturbed *tide* will ever reach below *datum*. Because of shallow water effects around the coast of the UK, LAT and HAT are not generally symmetrical about *mean sea level*. See also *highest astronomical tide*, HAT.

**Mean sea level, MSL**: The average level of the sea over a period of time long enough to remove variations in level due to *waves, tides and storm surges*. Used as a *datum* from which to measure or estimate changes in *still water level* due to *tides* and *storm surges*.

**Mean water depth**: See *water depth*.

**Mean zero-up-crossing period**: See *wave period*.

**Metocean**: Abbreviation of ‘meteorological and oceanographic’.

**Neap tide**: See *tides*.

**Peak frequency**: See *wave energy spectrum*.

**Probability of joint occurrence**: See *joint probability*.

**Refraction**: The process by which *wave* energy is redistributed as a result of changes in the wave propagation velocity due to variations in water depth.

**Residual currents**: The components of a *current* other than *tidal current*. The most important is often the *storm surge current*.

Mean flow or circulation is the residual averaged over a period greater than 10 days.
**Return period:** The average period of time between exceedances of a stated value of a metocean variable. See also *extreme value*.

**Sea state:** A general term for the wave conditions at a particular time and place. Parameters such as significant *wave height* and mean zero-up-crossing *wave period* are often referred to as ‘sea-state parameters’. A sea state is usually assumed to stay statistically stationary for a period of 3 hours. See also *wave sampling period*.

**Sea surface variance:** The mean-square elevation of the sea surface (with respect to *still water level*) due to waves. Proportional to the energy density per unit area of sea surface. See also *wave energy spectrum*.

**Significant wave height:** See *wave height*.

**Significant wave steepness:** See *wave steepness*.

**Site-specific measurements:** In the context of this report, measurements of a *metocean* variable made at the location or proposed location of an offshore installation.

**Spectrum:** See *wave energy spectrum*.

**Spring tidal amplitude:** See *tides*.

**Spring tidal current:** See *tides*.

**Spring tide:** See *tides*.

**Still water level:** The level of the surface of the sea in the absence of surface waves generated by the wind. Variations in still water level are principally due to *tides* and *storm surges*. See also *wave crest elevation*.

**Storm surge:** Irregular movement of the sea brought about by wind and atmospheric pressure variations. In UK waters, storm surges are usually generated by depressions passing from the Atlantic into Europe.

Storm surge elevation is the change from the predicted *tidal level* as a result of a storm surge. It can be positive or negative and, for design purposes, is defined as an *extreme value*.

Storm surge current is the *current* resulting from a storm surge. An *extreme value* is required for design purposes.

**Surface wind drift:** The *current*, in the top few metres of the water column, generated in direct response to the local wind blowing over the surface of the sea.

**Thermocline:** The relatively steep vertical temperature gradient sometimes present over part of the water column. Solar heating of the surface layers of the sea in summer generates seasonal thermoclines that disappear in winter. Permanent thermoclines can also be present at greater depths, usually indicating a boundary between different water masses.

**Tides:** Regular and predictable movements of the sea generated by astronomical forces. They can be represented as the sum of a number of harmonic constituents, each with different but known periods. In UK waters, the largest constituents are the lunar and solar semi-diurnal components (designated M2 and S2) with periods of 12.4 and 12.0 hours respectively.
Average spring tidal current is the *tidal current* corresponding to *spring tidal amplitude* (see below).

Spring tidal amplitude, STA is an indicator of the variation in still water level due to a typical spring tide. Defined as the change due to M2 and S2 only (see above). Amplitude is half the range.

Spring tides occur when M2 and S2 (see above) are in phase, and Neap tides when they are out of phase.

Tidal current is the *current* resulting from the *tides*. During a characteristic tidal current period, the current vector describes an ellipse with a maximum *current speed* and associated direction and a minimum speed and direction. The size of the ellipse changes with the progression of spring and neap tides.

Tidal level is the change in *still water level* brought about by tides. Measured relative to a *datum*.

**Voluntary observing fleet, VOF:** The ships of passage that transmit basic *metocean* data to the Meteorological Office.

Water depth: The vertical distance between the seabed and a defined *datum* near the sea surface, e.g. *mean sea level* in this report (giving ‘mean water depth’).

Waves: Taken in this report to refer to movements on the sea surface generated by wind and with *wave periods* of less than about 25 seconds.

Wave crest elevation, C: The vertical distance between the crest of a *wave* and *still water level*.

Wave direction: The mean direction from which wave energy is travelling.

Wave energy spectrum: A frequency-domain description of the whole *wave system* (or *sea state*). The wave system is assumed to consist of a large number of long-crested sinusoidal wave trains travelling independently but superimposed on each other. The omnidirectional spectral density function $S(f)$ is defined such that $S(f)\Delta f = \text{the sum of the sea surface variances}$ (proportional to energy per unit area) of the wave trains with frequencies between $f$ and $f + \Delta f$, where $\Delta f$ is a small frequency interval.

Peak frequency of a spectrum is the *wave frequency* corresponding to the maximum value of the omnidirectional spectral density function.

Wave exceedance diagram: A plot of the proportion of time for which the *wave height* is less than the value specified on the abscissa. Can be presented on a seasonal or all-year basis. Also called the ‘cumulative frequency distribution of wave height’.

Wave frequency: The number of waves passing a fixed point in unit time. See also *wave period*.

Wave height, $H$: In general, the vertical distance between the crest of one wave and the preceding trough. Only in unusual circumstances is it exactly twice the *wave crest elevation*.

Height of a zero-up-crossing wave is the vertical distance between the highest and lowest points on the water surface of a particular *zero-up-crossing wave*.

Significant wave height, $H_s$ is $4\sqrt{m}$, where $m$ is the *sea surface variance*. In sea states with only a narrow band of wave frequencies, $H_s$ is approximately equal to $H_{1/3}$ (the mean height of the largest third of the zero-up-crossing waves).
Extreme significant wave height, $H_{SN}$ is the significant wave height (see above) with a return period of $N$ years (e.g. 50 years for $H_{S50}$).

Extreme wave height, $H_N$ is the individual wave height (generally the zero-up-crossing wave height) with a return period of $N$ years (e.g. 50 years for $H_{S50}$).

**Wave hindcasting:** Estimating the wave characteristics at a specified time in the past using historic meteorological data.

**Wave period, $T$:** The time interval between successive waves. The period of a zero-up-crossing wave is the time interval between the two zero up-crossings which bound it. See also wave frequency.

Mean zero-up-crossing period, $T_z$, is calculated for a random sea by dividing the wave sampling period by the number of zero-up-crossing waves in the sampling period.

**Wave sampling period:** The relatively short period of time (usually 1000 seconds) for which wave elevation and/or other wave variables are measured in order to define the sea state.

**Wave scatter diagram or plot:** The bivariate probability distribution (or joint frequency distribution) of significant wave height, $H_s$, and mean zero-up-crossing wave period, $T_z$, of the measured sea states at a location. Other height and period parameters are occasionally used.

**Wave spectrum:** See wave energy spectrum.

**Wave steepness:** The ratio of the wave height to the wavelength. Significant wave steepness in deep water is the ratio of the significant wave height to the wavelength of a periodic wave whose period is the mean zero-up-crossing wave period.

**Zero-up-crossing wave:** The portion of a wave record (the time history of wave elevation) between adjacent zero-up-crossings. A zero-up-crossing occurs when the sea surface rises (rather than falls) through the still water level. Wave records are conventionally analysed on the basis of the zero-up-crossing waves they contain.

Height of a zero-up-crossing wave: See wave height.

Zero-up-crossing period: See wave period.
2. THE PARAMETERS

Table 1 may be used as a reminder of the relevant metocean design parameters.

<table>
<thead>
<tr>
<th>Parameter value required</th>
<th>Influences on values *</th>
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<td>Averaging time</td>
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<td>Vertical profile</td>
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<td>Extreme still water level variations</td>
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<td><strong>Currents</strong></td>
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<td>Averaging time</td>
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<td><strong>Temperatures</strong></td>
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<td>Extreme air temperatures, maximum and minimum</td>
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<tr>
<td>Extreme sea temperatures, maximum and minimum</td>
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* Note that geographical location and the season of the year influence the majority of the parameters
3. WINDS

3.1 INTRODUCTION

Wind is an important metocean parameter in the design of offshore installations for two reasons - a structure must be designed to withstand the forces exerted by the wind itself and the heights and directions of waves at the location depend on the speed and direction of the wind over some preceding period of time and a wider area.

To satisfy both uses, estimates of extreme wind speeds with no less than 50-year return periods are required with averaging times ranging from 3 seconds (i.e. an extreme gust value) to 24 hours. The estimates are referenced to a standard height of 10m above still water level but wind speeds at greater heights may be required.

Wind speeds with return periods less than 50 years are a necessary input to some aspects of detail design and can be estimated from Table 2. Additionally, the spectra of fluctuating wind gusts may be required; there are very little offshore measured data available although land-based data can be adapted with care for offshore use (see Section 11.4).

Table 2 Relationship between 50-year return wind speed and extreme wind speeds with different return periods

<table>
<thead>
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</table>

Source: Analysis of measurements over land (OTH 89 2994)

The values for the N-year return wind speed \(V_N\) in the table fit the relationship:

\[ V_N = 0.71(1 + 0.106 \ln N) V_{50} \]

To derive seasonal extremes, it is acceptable to evaluate the 5-year return wind speed for a particular month and apply the appropriate ratio for other required return periods. Relationships between seasonal and annual 50-year return wind speeds for a number of sea areas are given in Table 7.
3.2 SITE-SPECIFIC MEASUREMENTS (WINDS)

a) Criteria for use

A well-controlled series of wind measurements at the location of an offshore installation is a valuable source of data, although measurements taken over a short duration may give misleading estimates of long-term extreme wind speeds.

Extremes derived from short-term site-specific measurements should only be used in preference to the indicative values of Section 3.3 if care is taken to adjust the records to reflect long-period climatology; for example by analysing in conjunction with the record from a nearby site with at least 10 years of continuous hourly measurements (see Section 3.2 b) below).

The site-specific measurements should be made consistently throughout the period and in a manner suitable for estimating climatological extremes rather than for synoptic meteorology. In particular:

- the height of wind measurements above still water level must be known and must be sufficiently high to be clear of disturbances to the air flow from the wave surface
- the averaging time of the wind speed measurements must be known
- the anemometer must not be shielded.

Wind measurements at a land station, even if comparatively close to an offshore location, may be misleading because of the sharp gradient in wind speed near the coastline. If it is decided to use land measurements because offshore measurements are not available, allowance should be made for this effect.

b) Estimates of 50-year return wind speed

It is recommended that site-specific wind data are analysed in two stages to produce an estimate of extreme wind speed. The first stage is to use a recognised technique (such as fitting the data to a Weibull, Gumbel or log-normal distribution) to derive an extreme wind speed having a return period less than or of the same order as the available length of record, e.g. a return period of 2 or 5 years. The Weibull distribution has been used to predict the indicative values described in Section 3.3 a).

If 10 or more years of measurements are available at the location, the next stage is to extrapolate the 2 or 5-year return wind speed to a 50-year return speed using the standard ratios of Table 2. If the extent of wind speed measurements is shorter than 10 years, measurements made during a climatologically anomalous period may dominate the data set. The data may therefore not be typical of the long-term climate at the location and should not be extrapolated directly using the standard ratios. In these circumstances, the 50-year return wind speed should be obtained by multiplying the 2 or 5-year return speed by a site-specific ratio. This ratio may be obtained from data at a nearby reference site that has a record of suitable wind measurements extending over at least 10 years and preferably longer. The ratio is the 50-year return wind speed estimated from the full data set at the reference site divided by the 2 or 5-year return speed estimated from data measured at the reference site over the same shorter period for which measurements are available at the location of the installation. This ratio is only reliable if it has been calculated for a reference site close enough to the location to be synoptically correlated. A maximum separation of 180 km seems realistic.
3.3 INDICATIVE VALUES (WINDS)

a) Hourly wind speeds at 10m above sea level

Estimates of 50-year return hourly wind speeds are shown in Figure 1. The speeds are appropriate for a height of 10 m above still water level. The map gives no indication of the direction of the extreme wind.

Ocean Weather Stations, where wind speeds have been measured for many years at fixed locations, are shown •. Sites used for verification purposes are shown ○ (see OTH 89 299[4]).

Source: Analysis of VOF and instrumental data (OTH 89 299[4]). Details of the analysis method used are to be found in this reference.

Figure 1 Estimates of 50-year return omnidirectional hourly-mean wind speeds at 10 m above still water level

Estimates from Figure 1 are likely to be subject to a maximum error of ±2 m/s.
Estimates of wind speeds with return periods other than 50 years may be obtained by multiplying the 50-year return speeds by the relevant factor in Table 2.

b) Other averaging times

The relationships between 50-year return wind speeds with averaging times longer than 1 hour and the hourly speed are shown in Table 3.

Because the factors are the highest calculated at a number of sites where full measured data are available, estimates made using the factors at other locations should be accurate to within ±0 and ±2 m/s.

Estimates of 50-year return wind speeds with averaging times less than 1 hour are shown in Table 4. For each extreme hourly wind speed contour in Figure 1, the table gives corresponding wind speeds for a range of averaging times from 15 minutes to 3 seconds. Unlike wind speeds with averaging times greater than 1 hour, standard conversion factors cannot be applied for all wind speeds; the conversion factors are a function of drag coefficient which is itself a function of wind speed.

Estimates made using Table 4 data are likely to be accurate to within ±2 m/s.

c) Greater heights above sea level

Estimates of 50-year return wind speeds at heights up to 140 m above still water level are shown in Table 5. In the first section of the table, the wind speeds in the first column correspond with the even number contour values in Figure 1. In the other three sections of the table, the wind speeds in the first column are the appropriate corresponding values from Table 4.

Estimates made using Table 5 data are likely to be accurate to within ±2 m/s.

d) Directional wind speeds

The variation of 50-year return wind speed by direction is shown in Table 6 for 12 representative areas in UK designated waters. The representative areas are described in Figure 2. Values from Table 6 may be used in conjunction with values from Tables 3, 4 and 5 to estimate directional values of non-hourly 50-year return wind speeds at heights greater than 10 m.

Outside the representative areas, indicative values of directional extreme wind speeds can be established by further analysis of the VOF wind data held by the Meteorological Office. In the region of the North West Approaches, the directional extreme wind speeds are broadly similar to those in the adjacent representative areas (1, 11 and 12) but with marginally more sheltering in the direction of nearby land masses.

Estimates based on Table 6 data should be accurate to within ±2 m/s.

e) Seasonal variations

Estimates of the seasonal variation of 50-year return wind speed are shown in Table 7 for the same 12 representative areas of Figure 2. Again, the values may be used in conjunction with Tables 3, 4 and 5 and should be accurate to within ±2 m/s.
Table 3  Factors to convert the 50-year return hourly wind speeds of Figure 1 to 50-year return wind speeds with longer averaging times

<table>
<thead>
<tr>
<th>Averaging time (hours)</th>
<th>Multiplying factor</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>0.97 ±0.01</td>
</tr>
<tr>
<td>6</td>
<td>0.93 ±0.02</td>
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<tr>
<td>12</td>
<td>0.87 ±0.02</td>
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<tr>
<td>24</td>
<td>0.80 ±0.02</td>
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</tbody>
</table>

*Source: Analysis of measurements (OTH 89 299)*

Table 4  Relationships between the 50-year return hourly wind speeds of Figure 1 and 50-year return wind speeds with shorter averaging times

<table>
<thead>
<tr>
<th>Extreme wind speed (m/s) with an averaging time of:</th>
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<tbody>
<tr>
<td>(Hour)</td>
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</table>

*Source: Mathematical modelling (OTH 89 299)*
Table 5  Relationships between the 50-year return hourly wind speeds of Figure 1 and 50-year return wind speeds with shorter averaging times and at greater heights above sea level

<table>
<thead>
<tr>
<th>Extreme wind speed (m/s) at a height above still water level of:</th>
<th>10 m</th>
<th>20 m</th>
<th>40 m</th>
<th>60 m</th>
<th>80 m</th>
<th>100 m</th>
<th>120m</th>
<th>140 m</th>
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</table>

Source: Mathematical modelling (OTH 89 299)
### Table 6  Relationships between directional 50-year return wind speeds and omnidirectional 50-year return wind speeds at 12 representative areas in UK waters

<table>
<thead>
<tr>
<th>Area</th>
<th>Ratio of directional extreme to omnidirectional extreme from the direction of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>1</td>
<td>0.95</td>
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<tr>
<td>2</td>
<td>0.95</td>
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<td>3</td>
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<td>11</td>
<td>0.95</td>
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<tr>
<td>12</td>
<td>0.95</td>
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</tbody>
</table>

The 12 representative sea areas are identified in Figure 2
The wind directions are 45° sectors centred on the directions shown
Source: Analysis of VOF data (OTH 89 299)

### Table 7  Relationships between seasonal 50-year return wind speeds and annual 50-year return wind speeds at 12 representative areas in UK waters

<table>
<thead>
<tr>
<th>Area</th>
<th>Ratio of seasonal extreme to annual extreme for the season of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jan</td>
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<tr>
<td>1</td>
<td>1.00</td>
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<td>12</td>
<td>1.00</td>
</tr>
</tbody>
</table>

The 12 representative sea areas are identified in Figure 2
The periods are 3-month overlapping ‘seasons’ centred on the month shown
Source: Analysis of VOF data (OTH 89 299)
Figure 2  The twelve representative areas in UK, waters detailed in Tables 6 and 7
4. WAVES

4.1 INTRODUCTION

The predominant contribution to metocean forces on offshore installations generally comes from surface water waves. The information relating to waves used in the design should include heights, periods and directions; it should be clear what assumptions have been made, particularly those relating to limiting conditions. It should be borne in mind that the waves inducing maximum response in the structure as a whole may be different from those having the most severe effect on structural elements and that the maximum response of a compliant structure may be developed in response to waves other than the extreme amplitude design wave described below. It should also be noted that it will be lesser, more frequent waves which govern fatigue life.

a) Extreme amplitude design wave

The height of the extreme amplitude design wave considered should be not less than that which has a 50-year return period. For a fixed installation standing on the seabed, this wave may be the one which will develop maximum loads on the structure as a whole and on some, or all, of its principal elements. The maximum crest elevation of this wave will be needed to calculate the clearance height for the superstructure (see Sections 4.2b) and 4.3b)). The behaviour of a floating or compliant installation subject to the 50-year return wave also has to be examined even though maximum response of the structure may arise under other conditions.

The general methods for estimating the parameters of design waves are appropriate for deep water conditions only; modifications are necessary in shallow water. It may also be appropriate to consider seasonal variations in the parameters of design waves, e.g. for short-term deployments.

b) Extreme response design waves

Analysis may show that the maximum loads may be developed in response to a wave, or group of waves, lower than the extreme amplitude design wave described above; this is likely to apply particularly to floating installations but may also be significant for seabed supported installations and their principal elements. In the case of a floating or compliant installation, wave conditions other than the extreme amplitude design wave may also give minimum clearance from a part of the installation not designed to withstand wave impact.

c) Wave energy spectra

Alternative methods of carrying out load and stress analyses (which are described in Offshore Technology Report OTO 2001 013 on Loads) are based on the use of wave energy spectra discussed below.

A non-directional wave frequency spectrum represents the distribution with frequency of the sea surface variance in a given sea state. The sea surface variance is itself proportional to wave energy. For design purposes, wave spectra are used:

- to assess the relative importance of waves of different frequencies in exciting the response of compliant or resonant structures, or elements of structures
to determine the force spectrum in fatigue calculations using the spectral method.

Apart from severe storms, the wave spectrum in the open ocean is generally a complicated mixture of swell from distant storms, ‘old wind sea’ from recent nearby winds, and sea generated by present local wind. Site-specific data should preferably be used to establish these spectra but, in the absence of such data and to make the problem tractable, a generalised Pierson-Moskowitz spectrum (see below) is often fitted to the measured $H_s$ and $T_z$ - although there is little experimental evidence to justify this.

For extreme conditions throughout UK designated waters and for non-extreme conditions in the southern North Sea and other similarly confined waters, the JONSWAP spectrum with $\gamma = 3.3$ (see below) may be more appropriate.

In water depths less than $d_1$ (see Section 4.4) consideration should be given to the effects of finite water depth on wave spectra.

It is important to ensure that the method of simulation of waves with a specified spectrum is such that the wide variability experienced in the ocean is reproduced. Particular care and often lengthy or multiple simulations are necessary if wave groups are to be sampled adequately.

**The generalised Pierson-Moskowitz spectrum**

The generalised Pierson-Moskowitz spectrum is represented by:

$$S(f) = A f^{-5} \exp [-B f^{-4}]$$

where

- $f$ = wave frequency
- $S(f)$ = distribution of sea surface variance (in $m^2$/Hz)
- $A$ and $B$ = variables determined by the prevailing sea state.

Replacing $A$ and $B$ in terms of the sea state parameters, $H_s$ and $T_z$:

$$S(f) \approx 0.080 H_s^2 T_z (T_z f)^{-5} \exp [-0.318 (T_z f)^{-4}]$$

where

- $H_s$ = significant wave height of the sea state (in metres)
- $T_z$ = mean zero-up-crossing period of the sea state (in seconds).

The peak frequency, $f_p$, corresponding to the maximum value of $S(f)$, is given by:

$$f_p^4 = 4/5 B$$

**The JONSWAP spectrum**

The JONSWAP spectrum has been derived from measurements made in the North Sea off Denmark (Hasselmann et al, 1973). It describes fetch-limited growing seas in the absence of swell and is represented by:
\[ S(f) = Af^{-5} \gamma^{q} \exp \left[ -Bf^{-4} \right] \]

where

- \( A \) and \( B \) = variables determined by the prevailing sea state (not the same as \( A \) and \( B \) in the preceding section on Pierson-Moskowitz)

- \( \gamma \) = a variable peak enhancement parameter

- \( q = \exp \left[ \frac{(f - f_p)^2}{2\sigma^2 f_p^2} \right] \)

- \( f_p \) = the peak frequency, corresponding to the maximum value of \( S(f) \).

Measurements in the North Sea have shown that:

- \( \sigma = 0.07 \) for \( f \leq f_p \)
- \( \sigma = 0.09 \) for \( f > f_p \)

\( \gamma \) has a mean value of 3.3, but can vary by more than \( \pm 50\% \).

The two remaining unspecified parameters can be related to the parameters \( H_s \) (in metres) and \( T_z \) (in seconds) of the sea state to give the following expression for the JONSWAP spectrum:

\[ (f) = 0.0749 H_s^2 T_z (T_z f)^{-5} 3.3^q \exp \left[ -0.4567(T_z f)^{-4} \right] \]

where \( q = \exp \left[ \frac{(1.286 T_z f - 1)^2}{2\sigma^2} \right] \) and \( \sigma \) has the values indicated above.

The period \( T_p \) is that corresponding to the peak frequency \( f_p \) and is given by:

\[ T_p = \frac{1}{f_p} \]

For \( \gamma = 3.3 \), \( T_p \approx 1.286 T_z \).

**Directional spectra**

The directional wave spectrum, \( S(f, \theta) \), describes the distribution of surface variance with frequency, \( f \), and direction, \( \theta \), where \( \theta \) is the direction from which the wave component is travelling. The non-directional, or one-dimensional, spectrum is given by:

\[ S(f) = \int_{-\pi}^{\pi} S(f, \theta) d\theta \]

It is usual to express \( S(f, \theta) \) in terms of \( S(f) \) and a spreading function \( G(f, \theta) \), i.e.:
\[ S(f, \theta) = S(f) G(f, \theta) \]

where \( \int_{-\pi}^{\pi} G(f, \theta) \, d\theta = 1 \)

There is no general consensus on the form of \( G(f, \theta) \), but a commonly used expression is:

\[ G(f, \theta) = N \cos^{\frac{2\pi}{\theta_m}} \left( \theta - \theta_m \right) / 2 \]

where \( \theta_m \) is the dominant direction, and \( s \), a spreading factor, are both functions of \( f \). \( N \) is a normalising constant which ensures \( G(f, \theta) \) integrates to 1, and is given by:

\[ N = \frac{1}{2\sqrt{\pi}} \frac{\Gamma(s + 1)}{\Gamma(s + 0.5)} \]

where \( \Gamma \) is the gamma function.

For a simple analysis where a constant value of \( s \) independent of frequency is used, the value \( s = 10 \) is recommended. In these circumstances, \( N = 0.903 \).

d) Distribution of wave encounters

An estimate of the probable distribution of wave encounters that the installation is likely to experience during its service life is essential for assessing whether significant fatigue effects will develop in its structural elements (see Section 11).

4.2 SITE-SPECIFIC MEASUREMENTS (WAVES)

a) Criteria for use

The wave parameters used in design should ideally be based on a series of site-specific wave measurements. However, a short series of measurements at a location may give misleading results and wave parameters derived from site-specific measurements should not be used in preference to the indicative values of Section 4.3 unless there are at least 6 consecutive winter months of 3-hourly measurements available with a high level of data return. Close to the sites marked \( \otimes \) on Figure 3, where the indicative values are relatively well established, site-specific measurements should only be used in preference if the data set is longer than 3 years or if a shorter data set has been calibrated against an adjacent well-established site.

Where a data set is available but is too short to give wave parameters satisfying the above requirements, its output is useful as an independent check on the indicative values. Significant discrepancies between indicative values and parameters derived from site-specific measurements should be resolved.

Sea state parameters obtained from the results of a wave hindcasting model that has been validated by comparison with nearby instrumental wave data may be used in place of direct wave measurements provided that the duration of the hindcast exceeds about 5 years or it can be shown to have taken into account a statistically adequate sample of extreme storm events.
b) **Estimation of extreme crest elevations and extreme wave heights**

A programme of site-specific wave measurements yields values of significant wave height, $H_s$, associated mean zero-up-crossing period, $T_z$, and usually other measures of period derived from the spectrum. These parameters are typically measured at 3-hourly intervals over a wave sampling period of at least 1000 seconds. If sufficient years of data are available, an asymptotic extreme value analysis should be used to obtain an estimate of the significant wave height having a 50-year return period ($H_{s50}$). Otherwise, individual values of $H_s$ from the data set should be fitted to a recognised probability distribution and this should be used to obtain an estimate of the 50-year return value. The choice between the different distributions (e.g. Fisher-Tippett, Weibull, etc) should be made on the basis of goodness of fit or other relevant considerations. The Fisher-Tippett I distribution has been used to calculate the indicative values described in Section 4.3 (OTH 89 300)(5).

The accuracy with which $H_{s50}$ can be estimated in this way increases with the number of years for which measured data are available. For example, at the Seven Stones Light Vessel (50°N, 6°W) the standard error of estimates of $H_{s50}$ based on 1-year blocks of data is about 10% of the long-term value. For data blocks longer than 1 year the standard error can be expected to decrease in the ratio $1/N^{1/2}$, where $N$ is the number of years of available data.

In deep water (where the ratio of water depth to the wave length is greater than about 0.25 - see Section 4.4) the elevation above still water level of the crest of the wave with a 50-year return period ($C_{50}$) may be estimated by:

$$C_{50} = 1.03 H_{s50}$$

The crest-to-trough wave height ($H_{50}$) of the corresponding individual wave may be estimated by:

$$H_{50} = 1.86 H_{s50}$$

Table 8 shows the relationships between $H_{s50}$ and $C_N$ and $H_N$, i.e. crest elevations and wave heights with return periods other than 50 years. The estimates for wave heights are based on correlation between crest elevation and an estimate of the adjacent trough depth and so are less accurate than the estimates for crest elevation.
Table 8  Factors to derive crest elevations and heights of individual waves with return periods between 5 and 10,000 years from values of $H_{s50}$

<table>
<thead>
<tr>
<th>Return period, N (years)</th>
<th>N-year return value of crest elevation above still water level, $C_N$</th>
<th>N-year return value of individual wave height (crest to trough), $H_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.86 $H_{s50}$</td>
<td>1.56 $H_{s50}$</td>
</tr>
<tr>
<td>10</td>
<td>0.91 $H_{s50}$</td>
<td>1.65 $H_{s50}$</td>
</tr>
<tr>
<td>50</td>
<td>1.03 $H_{s50}$</td>
<td>1.86 $H_{s50}$</td>
</tr>
<tr>
<td>100</td>
<td>1.08 $H_{s50}$</td>
<td>1.95 $H_{s50}$</td>
</tr>
<tr>
<td>1000</td>
<td>1.25 $H_{s50}$</td>
<td>2.25 $H_{s50}$</td>
</tr>
<tr>
<td>10,000</td>
<td>1.42 $H_{s50}$</td>
<td>2.57 $H_{s50}$</td>
</tr>
</tbody>
</table>

Values in the table are based on the relationships:

$C_N = 0.74 (1 + 0.1 \ln N) H_{s50}$

$H_N = 1.34 (1 + 0.1 \ln N) H_{s50}$

These relationships are a good approximation in UK waters (OTH 89 300) but should be used with care for water depths less than $d_1$ (as defined in Section 4.4).

A good estimate for the significant wave height exceeded 12 times a year, $H_{1/12}$, is $H_{1/12} = 0.52H_{s50}$. The individual wave height exceeded 12 times a year may be assumed to be 84% of the individual wave height exceeded once a year, $H_1$. The derivations of these relationships are to be found in OTH 89 300, where the values of $H_1$ for a number of sites are also tabulated.

c) Associated wave periods

Neither the value of the mean zero-up-crossing period ($T_z$) associated with the extreme sea state nor the period ($T_{ass}$) of the individual extreme wave can be estimated directly from measurements. Experience in UK waters suggests that significant wave steepness of extreme seas usually lies in the range 1/20 to 1/16. On this basis, $T_z$ can be assumed to lie in the range:

$$3.2 (H_{s50})^{1/2} < T_z < 3.6 (H_{s50})^{1/2}$$

where $H_{s50}$ is in metres and $T_z$ is in seconds.

When the fetch generating the design wave is limited, $T_z$ may be smaller. With a fetch less than 250km, the minimum period may be as low as $2.8(H_{s50})^{1/2}$.

Experimental and theoretical evidence shows that $T_{ass}$ can take a wide range of values for a specified $T_z$, generally within the range:

$$1.05 T_z < T_{ass} < 1.4 T_z$$

(See also Section 4.3 b))

The effect on structural design should be considered for all values within these ranges. In addition, periods outside the ranges should also be considered if they correspond with a peak in the structure’s response function.
d) **Directional distribution of the extreme wave**

Structural advantage may be taken from the predominant direction of the extreme wave if a sufficient quantity of observational or proven hindcast evidence has been assembled to enable the likely directional distribution to be predicted with confidence. Available data should be distributed between, for example, eight $45^\circ$ directional sectors orientated so that the peak of the angular distribution lies in the middle of one sector - the prevailing sector. The data can then be considered sufficient if the number of data points in the prevailing sector is at least as large as the number of data points that would satisfy the criteria for all directions in Section 4.2 a).

### 4.3 INDICATIVE VALUES (WAVES)

a) **Significant wave heights**

Estimates of 50-year return significant wave heights, $H_{s50}$, are shown in Figure 3 (the derivation of which is described below). The estimates are values which would be expected if the effects of detailed bottom topography were unimportant. In particular, they do not take full account of refraction, shoaling and wave breaking which may be important where ‘shallow water’ conditions prevail (see Section 4.4).

Close to the wave measurement sites marked with an $\otimes$ on the figure, the 95% confidence limits of the estimates of $H_{s50}$ are estimated to be $\pm10\%$, reflecting the relatively long data sets available at these sites and a relatively high level of consistency between estimates from adjacent sites. Elsewhere, accuracies are more likely to be $\pm20\%$.

No indication can be given for the directions of these waves; they should be assumed to come from any direction unless a preferred direction can clearly be established by site-specific studies, e.g. by using measured or hindcast directional data or by taking into account the wind rose and fetch.

Figure 3 is based on the analysis of measurements at 41 sites, including oil platforms (OTH 89 300)$^{(5)}$. Data from all the sites have been analysed consistently, using the Fisher Tippett I (Gumbel) distribution, which was fitted by applying the method of moments to the cumulative distribution function values at 0.5m intervals. In most cases, the bulk of the measured distribution is well fitted by this functional form: however the top 0.1% of the data frequently exhibit significant departures from this form, which are not fully understood. This matter is of importance, since it is only these data points which are used in any analysis based on the use of monthly or annual extreme events. Such analyses tend to lead to significantly lower values of $H_{s50}$ than those shown in Figure 3. Two alternative explanations have been postulated for this behaviour. According to the first, there is some physical mechanism which tends to limit the height of extreme waves, so that these do not belong to the same statistical population as normal waves. According to the second, the available data sets are defective, in that the higher waves are selectively lost. It can be shown that the loss of half of the most extreme values (i.e. of those lying in the top 0.1%) is sufficient to account for the observed departure from the FT-I distribution. Since the overall data loss in the available records is seldom less than 5% in each winter month, it is not possible to exclude this interpretation. In view of this uncertainty, it is difficult to recommend lower indicative values than those shown in Figure 3. However, this does not mean that a case cannot be made for lower values.

Using the values of $H_{s50}$ derived from measurements as a starting point, the contours on the map have been drawn subjectively taking into account the quantity of data used to derive $H_{s50}$ at each site, its general spatial
consistency and the direction of wave height contours derived from modelling $H_{s50}$ from wind speed and water depth (see OTH 89 300\textsuperscript{(5)} for full details).

\textbf{b) Crest elevation, wave heights and periods}

Corresponding 50-year return crest elevations and individual wave heights may be estimated from the values of $H_{s50}$ in Figure 3 using the relationships quoted in Table 8, e.g.

$$C_{50} = 1.03H_{s50} \text{ and } H_{50} = 1.86H_{s50}$$

Table 8 also describes the relationship between $H_{s50}$ and extreme crest elevations and extreme wave heights with return periods other than 50 years.

The mean zero-up-crossing period, $T_z$, associated with $H_{s50}$ and the period, $T_{ass}$, associated with $H_{s50}$ may be estimated as described in Section 4.2 c).

This document does not contain a contour map showing the period of the extreme wave. The conversion factors giving ranges for $T_z$ and $T_{ass}$ based on $H_{s50}$ are considered to be a more accurate presentation. Values for $T_{ass}$ of 1.27 $T_z$ and 1.073 $T_z$ (based on the analysis of experimental data and theoretical considerations) have been reported by Bell 1972\textsuperscript{(11)} and Longuet-Higgins 1983\textsuperscript{(12)} respectively, and a range of values comfortably wider than these limits is quoted in Section 4.2 c).
Contours are in metres.

Wave measurement sites are marked •. Measurement sites where accuracy of estimates is likely to be relatively high are marked @ (see Section 4.3 a)).

Shallow water effects should be taken into account where applicable (see Section 4.3 a) and 4.4).

Source: Analysis of measured wave data and wind data (OTH 89 300).

Figure 3 Estimates of 50-year return significant wave heights, $H_{S_{50}}$

4.4 SHALLOW WATER EFFECTS

The effect of the sea bed on the velocity of propagation of waves starts to become of practical significance when the ratio of the water depth to the wave length is less than about 0.25. In estimating the parameters of extreme waves, different shallow water effects need to be considered depending on the water depth. Two broad areas can be defined by limiting water depths, $d_0$ and $d_0$. The significance of these depths is explained in detail below but they have approximate values:
\[ d_1 = 7.5 \ H_{s50} \text{ and } d_0 = 2.5 \ H_{s50} ' \]

where

- \( H_{s50} \) = the 50-year return significant wave height from Figure 3
- \( H_{s50} ' \) = the significant wave height from Figure 3 modified if necessary by the results of the refraction study described below.

The derivation of the depth \( d_1 \), where wave breaking begins to be of importance, is based on the usual engineering criterion for a wave to break, i.e. the wave height \( H = 0.78 \) depth. The highest wave in 3 hours (having a probability of exceedance of 63%) has been defined as \( 1.86H \). This leads to the relation \( d_1 = 2.5H_{s50} \) (to the nearest 0.5 in the multiplying constant). In the southern North Sea, assuming \( H_{s50} = 9m \), this gives a value for \( d_0 \) of 22.5m. If the criterion is set at a level where the highest wave has only a 1% probability of exceedance, and assuming a significant wave steepness of 1/18, the relation becomes \( 3.0 \ H_{s50} \) and \( d_0 = 27.0m \).

The derivation of the depth \( d_1 \) below which shallow water effects should be considered, is based on the criterion that a 10% change in the wave phase velocity will be significant. For the spectral peak of a generalised Pierson-Moskowitz\(^{(8)}\) spectrum this corresponds to a depth-to-wavelength ratio of 1/2.5 which leads to \( d_1 = 7.4 \ H_{s50} \). Adopting the same accuracy as that for \( d_0 \), the relationship for \( d_1 \) becomes \( d_1 = 7.5H_{s50} \). In storm conditions, the spectrum is probably JONSWAP\(^{(9)}\) and in this case the criterion \( d_1 = 7.5H_{s50} \) leads to a change in phase velocity of approximately 8%.

At locations with water depths between \( d_1 \) and \( d_0 \) when the bottom topography is sufficiently variable or if the wave crests are not parallel to the bottom contours, the possibility should be considered that wave propagation may be modified by shoaling or refraction. If a wave propagation study is to be carried out it should be based on directional wave spectra. Standard parametric equations may be used but, if the location is exposed to the open ocean, the possibility of effectively focusing uni-directional swell should also be considered. Where refraction is unimportant, deep water wave heights may be used unmodified but with crest elevations given by appropriate shallow-water wave theory.

At depths less than \( d_0 \) (or where a shoal of this depth or less lies between the location and deep water) the full range of shallow water effects should be considered:

- refraction due to bottom topography
- refraction due to currents
- steepening of waves moving into shallower water
- steepening of waves travelling onto an opposing current
- loss of wave energy due to breaking and bottom friction.

In relatively very shallow water, e.g. in the area of the Dogger Bank, the design wave may be entirely depth limited due to breaking.

### 4.5 SEASONAL VARIATIONS (WAVES)

At present there are no generally available indicative data for seasonal variations of wave climate. In the absence of site-specific information, the seasonal variation of the wind climate may be used as a basis for deriving the seasonal variation of the wave climate.
5. WATER DEPTHS AND SEA LEVEL VARIATIONS

5.1 INTRODUCTION

The overall depth of water at any location consists of the mean depth - defined as the vertical distance between the sea bed and an appropriate near-surface datum - and a fluctuating component which varies with changes in still water level.

The fluctuations are due principally to tides and storm surges. Tidal variations are regular and predictable, bounded by highest astronomical tide, HAT, and lowest astronomical tide, LAT. Storm surges, which are meteorologically generated and hence essentially irregular, are superimposed on the tidal variations, so that total still water levels above HAT and below LAT may occur.

5.2 SITE-SPECIFIC MEASUREMENTS (WATER DEPTHS)

The best estimates of the mean water depth and of the fluctuations (HAT, LAT, extreme surge elevation and extreme total still water level) are derived from site-specific measurements with an offshore tide gauge measuring pressure from the sea bed. Accurate estimates require at least one complete year - and preferably several years - of high quality hourly data from the location.

The recommended analysis procedure (Pugh and Vassie 1979) requires:

- subtraction of atmospheric pressure from pressure-gauge readings
- conversion of pressure measurements to equivalent depths, using density/temperature corrections
- harmonic tidal analysis, giving values of all significant tidal constants and the mean depth
- prediction of tides over 19 years and extraction of HAT and LAT
- subtraction of predicted tides from measured levels, giving a time series of hourly storm surge elevations
- separate statistical analyses of the tidal and storm surge elevations
- combination of the frequency distributions of tidal and surge elevation to give the required probabilities of total still water level.

A good quality, calibrated, pressure sensor should give instantaneous measurements of water pressure accurate to 0.01%, but errors associated with settlement of the instrument and conversion of pressure to depth (using salinity and temperature data) may reduce the accuracy of the derived mean depth to about 0.1m. The magnitude of errors in the estimates of extreme surge and total still water level obtained from the joint probability analysis depends on a number of factors, including the accuracy (in magnitude and timing) of the observations and the duration of the measurements. A single large surge event may have a significant influence on the estimates of extreme surge and total still water level implying greater uncertainty in these parameters than in the tidal values. A conservative assumption is that the estimate of extreme still water level (relative to mean sea level, MSL) from an input of one year of high quality hourly data should be within 10% of the true value.
Periods of measurement shorter than one year may give acceptable estimates of the mean depth and tidal constants. However, the tidal constants derived from one month of data and hence the spring tidal amplitude, STA (see Section 1.6 - Definitions), could be in error by as much as 10% depending on location, although the error may be reduced if the analysis makes proper use of relationships from a nearby site with at least a year of good quality data. A site-specific value of STA, if available, may be used in place of the indicative value in the procedures described in Sections 5.3 b) to d) below. Direct estimates of extreme surges and extreme still water levels from less than one year of data are likely to be unreliable, but level measurements of short duration and surges derived from them are useful as independent checks on the indicative values.

When tide gauge measurements have not been made and mean depth has been determined by local soundings, corrections must be made for the state of the tide by reference to tide tables, co-tidal charts or the nearest available tide gauge. The overall error in mean depth measured in this way is likely to be about 2m and hence depth measurement by soundings is not recommended.

5.3 INDICATIVE VALUES (WATER DEPTHS)

a) Mean water depth

Although Admiralty charts are available showing mean water depths with respect to Chart Datum (i.e. LAT), most of the northern part of the North Sea was last surveyed in the late nineteenth and early twentieth centuries. In areas that have been surveyed more recently, water depths should be accurate to about 0.1m but the older charts may be more than 2m in error, with depths most likely to be too shallow. Data from this source should only be used to establish mean water depth if all steps have been taken to ensure that its accuracy is adequate.

b) Tidal levels

The levels of HAT and LAT may be estimated at any location from Figure 4 and Table 9. Figure 4 shows the variation of spring tidal amplitude, STA, and Table 9 lists the factors, T+ and T−, that relate STA to HAT and LAT at eight reference ports around the UK coast.

The level of HAT or LAT relative to mean sea level, MSL, is obtained by multiplying the STA from Figure 4 by the appropriate factor from Table 9 for the nearest port. If the location is close to two or more ports, a weighted average of factors should be used according to the distances between the ports and the offshore location.

Because Figure 4 is based on a substantial data set of offshore and coastal measurements, errors in STA should not generally exceed 10%. The estimates of the correction factors used to derive HAT and LAT rely on relationships established at the reference ports and the likely errors close to the ports should be small, increasing with distance from them to give errors in the open sea of 10%. At locations where STA is small, its plotted distribution will not be similar to those of LAT and HAT, so that larger percentage errors will arise.

c) Storm surge elevations

Estimates of 50-year return positive storm surge elevation are shown in Figure 5. The distribution is based on results from a numerical storm surge model adjusted to fit the values derived from observations at seven of the reference ports in Table 9 (excluding Immingham).
Errors in the distribution may arise from a number of sources. Assumptions concerning surge conditions along the open-sea boundaries of the model suggest that the results should be treated with caution within about 100km of the shelf edge and near the Skagerrak. Limitations in the sample of simulated surge events imply greater-than-average uncertainty in the Celtic Sea and western English Channel. Some of these basic deficiencies are countered by the adjustment of model results to fit observations so that, as with tidal levels, overall errors should be small near the seven reference ports and increasing with distance from them. Independent estimates for direct comparison are sparse (only two offshore) but indicate errors of less than 10%.

\[ \text{Spring tidal amplitude is half the spring tidal range} \]
\[ \text{Contours are in metres.} \]
\[ \text{Dotted line is the 100 fathom (183 m) depth contour} \]
\[ \text{Source: Observation and numerical model simulations (OTH 89 299)}^{(4)} \]

**Figure 4** Spring tidal amplitudes, STA
The elevations are deviations from the expected tidal level
Contours are in metres
Dashed line is the 100 fathom (183m) depth contour
Source: Numerical model simulations and observations (OTH 89 2999) (4).

Figure 5  Estimates of 50-year return positive storm surge elevations
Table 9  Factors to obtain HAT, LAT and 50-year return still water levels from Figure 4 and Figure 5

<table>
<thead>
<tr>
<th>Reference port</th>
<th>Conversion factors (see notes below)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T^\ast$</td>
</tr>
<tr>
<td>Newlyn</td>
<td>1.27</td>
</tr>
<tr>
<td>Fishguard</td>
<td>1.48</td>
</tr>
<tr>
<td>Malin Head</td>
<td>1.44</td>
</tr>
<tr>
<td>Stornoway</td>
<td>1.36</td>
</tr>
<tr>
<td>Lerwick</td>
<td>1.61</td>
</tr>
<tr>
<td>Aberdeen</td>
<td>1.30</td>
</tr>
<tr>
<td>Immingham</td>
<td>1.24</td>
</tr>
<tr>
<td>Southend</td>
<td>1.24</td>
</tr>
</tbody>
</table>

$T^\ast = \frac{\text{Level of HAT relative to MSL}}{\text{Spring tidal amplitude}}$

$T^- = \frac{\text{Level of LAT relative to MSL}}{\text{Spring tidal amplitude}}$

$E_{50} = \frac{\text{Estimate of 50-year maximum total still water level relative to MSL}}{\text{Spring tidal amplitude + 50-year positive storm surge elevation}}$

$R = \frac{\text{Estimate of 50-year minimum total still water level relative to MSL}}{\text{Estimate of 50-year maximum total still water level relative to MSL}}$

Source: The factors have been derived empirically (OTH 89 299)$^{(4)}$

Estimates of positive surge elevations with return periods other than 50 years may be obtained by multiplying the 50-year return value by:

$$0.72 \ (1 + 0.1 \ \text{ln} \ N)$$

where $N$ is the return period in years.

The factors 0.72 and 0.1 in this expression are means of the values at the reference ports. Use of this general expression throughout UK designated waters may introduce additional errors of the order of 10% compared with the use of the appropriate site-specific formula at any location.

d) Tide and surge combined

The 50-year return maximum and minimum total still water level may be estimated from the STA (Figure 4), the 50-year return surge elevation (Figure 5) and factors from Table 9.

For any location, the 50-year return maximum total still water level (relative to MSL) is found by multiplying the sum of STA and the 50-year return surge elevation by the factor $E_{50}$ in Table 9 for the nearest reference port. Where appropriate the weighted average of factors for two or more reference ports should be used.
The 50-year return minimum total still water level is found by multiplying the result by the factor R from Table 9. Note that R is not exactly -1, since extreme maximum and minimum levels are not symmetrical about MSL.

Errors in the estimates of extreme total levels arise for the reasons indicated in Section 5.3b) and c) above. Again, the scaling based on observed values at the reference ports should give overall errors increasing with distance from the ports. For the two offshore sites for which independent estimates exist, the differences between site-specific values and the indicative values are:

- Northeast of Shetland  maximum -1%  minimum -3%
- Inner Dowsing  maximum +3%  minimum +10%.

From these and other examples it can be assumed that the errors are not likely to exceed 10%.

Estimates of maximum total still water levels with return periods other than 50 years may be obtained by multiplying the 50-year return value by the relevant factor from Table 10. The factors 0.89 and 0.03 in the formula in the footnote to the table are means of the values at the reference ports. Use of these general factors throughout UK designated waters may introduce additional errors of the order of 5% compared with the use of the appropriate site-specific factors. However, errors at Southend are of the order of 20%, suggesting that the general factors should not be used where tide-surge interaction is significant.

### Table 10  Relationship between 50-year maximum total still water level and extreme maximum totals with different return periods

<table>
<thead>
<tr>
<th>Return Period, N, (years)</th>
<th>N-return level / 50-year return level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/12</td>
<td>0.83</td>
</tr>
<tr>
<td>1</td>
<td>0.89</td>
</tr>
<tr>
<td>2</td>
<td>0.91</td>
</tr>
<tr>
<td>5</td>
<td>0.93</td>
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<tr>
<td>10</td>
<td>0.95</td>
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<tr>
<td>20</td>
<td>0.97</td>
</tr>
<tr>
<td>50</td>
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<td>100</td>
<td>1.01</td>
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<td>200</td>
<td>1.03</td>
</tr>
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<td>500</td>
<td>1.06</td>
</tr>
<tr>
<td>1000</td>
<td>1.07</td>
</tr>
<tr>
<td>10000</td>
<td>1.14</td>
</tr>
</tbody>
</table>

* An average return period of one month making no allowance for seasonal variations

Values in the table are based on the relationship: \( L_N = 0.89(1 + 0.03 \ln N) L_{50} \)

Source: OTH 89 29944
e) **Datum changes**

Indicative values of HAT, LAT and extreme total still water level obtained by the methods described in Sections 5.3b) and d) are relative to MSL. The levels may be referred to LAT or any other datum, but it is essential that this is done as the final stage in the calculation. For example, to relate an extreme maximum total still water to LAT:

\[
\text{level (to LAT)} = \text{level (to MSL)} - \text{LAT (to MSL)}
\]

where the values on the right hand side are those derived in Sections 5.3 d) and b) respectively.

5.4 **LONG-TERM CHANGES (WATER DEPTHS)**

The mean water depth is not itself fixed but can vary with the length of the period of measurements from which it has been derived. Fluctuations of a few centimetres may occur from year to year, and the seabed may subside due to reservoir depletion. In addition, there is a general tendency in UK waters for MSL (and hence mean water depth) to rise by about 0.3m per century. The effect of such changes over the lifetime of an installation should be considered.

5.5 **SEASONAL VARIATIONS (WATER DEPTHS)**

Spring tidal high and low water levels vary through the year. The largest spring tides tend to occur within about a month of the spring and autumn equinoxes. An indication of the highest and lowest tidal levels during a specific period may be obtained by making use of information extracted from tide tables with an adaptation of the method of Section 5.3b). Factors equivalent to \( T^+ \) and \( T^- \) in Table 9 may be obtained by taking the highest and lowest predicted tide in the given period at a suitable nearby port from the tide tables, adjusting the datum to MSL (or mean tide level if MSL is not known) and dividing the adjusted values by STA. These factors can then be used to scale STA at the offshore location to give the required estimates.

Storm surges also vary seasonally, being generally larger and more frequent in the period September to April, as illustrated for Immingham in Table 11. Because there are no time series of measurements long enough to permit such analyses for offshore locations it is not clear if this quantitative behaviour applies generally.

The probability distribution of extreme total still water level also varies seasonally, but the analyses required to derive the variations have not been carried out and the differing behaviour of tide and surge components makes it difficult to suggest how they should be combined to provide the variation. It seems probable that extremes of total still water level during the season May to August should be less severe than at other times, but this cannot be quantified.
**Table 11  Seasonal storm surge residuals measured at Immingham, 1964-1981**

<table>
<thead>
<tr>
<th>Month</th>
<th>Extreme hourly-mean storm surge residuals * (metres)</th>
<th>As proportion of peak month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>0.83</td>
<td>0.95</td>
</tr>
<tr>
<td>Feb</td>
<td>0.73</td>
<td>0.84</td>
</tr>
<tr>
<td>Mar</td>
<td>0.71</td>
<td>0.82</td>
</tr>
<tr>
<td>Apr</td>
<td>0.63</td>
<td>0.72</td>
</tr>
<tr>
<td>May</td>
<td>0.30</td>
<td>0.34</td>
</tr>
<tr>
<td>Jun</td>
<td>0.28</td>
<td>0.32</td>
</tr>
<tr>
<td>Jul</td>
<td>0.31</td>
<td>0.36</td>
</tr>
<tr>
<td>Aug</td>
<td>0.34</td>
<td>0.39</td>
</tr>
<tr>
<td>Sep</td>
<td>0.56</td>
<td>0.64</td>
</tr>
<tr>
<td>Oct</td>
<td>0.64</td>
<td>0.74</td>
</tr>
<tr>
<td>Nov</td>
<td>0.87</td>
<td>1.00</td>
</tr>
<tr>
<td>Dec</td>
<td>0.82</td>
<td>0.94</td>
</tr>
</tbody>
</table>

*Storm surge elevations with a probability of exceedance of once in 200 hours*
6. CURRENTS

6.1 INTRODUCTION

The current at any location and time is the vector sum of tidal and non-tidal, i.e. residual, components. Tidal currents are regular and predictable and the maximum tidal current is associated with the highest or lowest astronomical tide, HAT or LAT. Residual currents are irregular but at most locations the largest residual to be considered is likely to be the extreme storm surge current. Other residuals include short period currents and long period, or ‘mean’, current. Table 12 gives a general indication of the range of current speeds which can be expected in the continental shelf seas around the UK.

Extreme currents are discussed in this section in terms of depth-averaged values and vertical profiles. The special problems of estimating currents in the deeper waters of the continental slope are described in Section 6.5.

Table 12  Range of maximum current speeds in the Continental Shelf seas around the UK

<table>
<thead>
<tr>
<th>Current</th>
<th>Range of maximum speed (m/s)</th>
<th>Period</th>
<th>Relevant Section</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal depth-averaged</td>
<td>0.3 - 2.5</td>
<td>12.4 hours</td>
<td>6.3 a)</td>
<td>For spatial variation see Figure 6.</td>
</tr>
<tr>
<td>Storm surge depth-averaged</td>
<td>0.2 - 1.4 *</td>
<td>2 - 10 days</td>
<td>6.3 c)</td>
<td>For spatial variation see Figure 9. More extreme in winter</td>
</tr>
<tr>
<td>Surface wind drift</td>
<td>0.9 - 1.2 *</td>
<td>1 - 2 days</td>
<td>6.3 d)</td>
<td>For spatial variation see Figure 1, Section 3. More extreme in winter</td>
</tr>
<tr>
<td>Internal waves</td>
<td>&lt; 0.4 *</td>
<td>3 minutes</td>
<td>6.3 g)</td>
<td>In the unshaded areas of Figure 8, particularly near the shelf edge. May - October</td>
</tr>
<tr>
<td>Inertial currents</td>
<td>&lt; 0.2 *</td>
<td>14 - 16 hours</td>
<td>6.3 g)</td>
<td>In the unshaded areas of Figure 8. May - October</td>
</tr>
<tr>
<td>Currents along fronts</td>
<td>&lt; 0.3 *</td>
<td>Long period</td>
<td>6.3 g)</td>
<td>At the boundaries of the shaded areas in Figure 8. May - October</td>
</tr>
<tr>
<td>Circulation</td>
<td>&lt; 0.15 *</td>
<td>Longer than 10 days</td>
<td>6.3 g)</td>
<td></td>
</tr>
</tbody>
</table>

* 50-year return value

* Maximum observed but higher speeds may be possible
6.2 SITE-SPECIFIC MEASUREMENTS (CURRENTS)

Site-specific measurements of currents at the location of an installation may be used either as the basis for independent estimates of likely extremes or to check the indicative values of tidal, storm surge and other residual currents. A suitable analysis of only 1 month of site measurements may give a more accurate estimate of the maximum speed of the average spring tidal current (see Section 1.6 - Definitions) than the indicative values of Section 6.3a). The same data will also provide an estimate of the residual current and a check that the indicative values of extreme storm surge current and extreme total current have not been exceeded. To predict 50-year return residual current and total current from site-specific data alone, it is necessary to have a high quality data set extending over at least 1 year, and preferably longer. If such data are available, the recommended method of estimating the extreme currents is the joint probability method of Pugh and Vassie 1979 (13) and Pugh 1982 (14).

Measured vertical profiles of tidal current or storm surge current may be used in place of the profiles described in Section 6.3 b) and d) provided current measurements to satisfy the above requirements have been made at 3 or more representative levels in the relevant portion of the water column.

Significant discrepancies between indicative values and site-specific values should be resolved.

Where site-specific measurements satisfying the above requirements are available for the maximum speed of the spring tidal current and/or the 50-year return storm surge current, they should be combined in the manner described in the following sections for indicative values.

6.3 INDICATIVE VALUES (CURRENTS)

a) Tidal currents - depth-averaged values

The depth-averaged maximum tidal current at any location - due to HAT or LAT - may be estimated on the basis of Figure 6 and Table 13. The direction of the current is indicated in Figure 7. The values in Figure 6 are estimates of the maximum depth-averaged flow of an average spring tidal current, and the factors in Table 13 relate these currents to the maximum tidal currents. The factors have been derived from elevation records at eight reference ports around the UK coast by taking the larger of $T^+$ and $T^-$ from Table 9 in Section 5.

Table 13 Factors to obtain maximum tidal current (due to HAT or LAT) from Figure 6 data

<table>
<thead>
<tr>
<th>Reference port</th>
<th>Conversion factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newlyn</td>
<td>1.28</td>
</tr>
<tr>
<td>Fishguard</td>
<td>1.48</td>
</tr>
<tr>
<td>Malin Head</td>
<td>1.44</td>
</tr>
<tr>
<td>Stornoway</td>
<td>1.49</td>
</tr>
<tr>
<td>Lerwick</td>
<td>1.61</td>
</tr>
<tr>
<td>Aberdeen</td>
<td>1.47</td>
</tr>
<tr>
<td>Immingham</td>
<td>1.33</td>
</tr>
<tr>
<td>Southend</td>
<td>1.24</td>
</tr>
</tbody>
</table>

Source: See Table 9
Contours are in m/s.
See Section 6 for definition of spring tidal current.
Dotted line is the 100 fathom (183 m) depth contour
Source: Observations (OTH 89 299).

Figure 6  Estimates of maximum depth-averaged flow of an average spring tidal current
Contours are in degrees clockwise relative to north or south.
O° and 180° are the same direction.
Dotted line is the 100 fathom (183 m) depth contour.
Source: Observations (OTH 89 299).

Figure 7  Direction of the maximum flow of the average spring tidal current

The estimate is obtained by multiplying the current speed from Figure 6 by the appropriate factor from Table 13 for the nearest port. If the location is close to two or more ports, a weighted average of factors should be used according to the distances between the ports and the offshore location.

Estimates derived from Figure 6 should be accurate to within ±15%. The estimates of the maximum current due to highest astronomical tides are more uncertain since they assume that the tidal currents are predominantly twice-daily and that they behave like the tidal elevations. For most locations these estimates
should be accurate to within ±20%. However, daily tidal currents can be comparable in strength with the twice-daily along the shelf edge from the west of Ireland to the Norwegian Trench, a feature not observed in tidal elevations. Here, the maximum tidal current will be underestimated, possibly by as much as 0.2m/s.

b) Tidal currents - vertical structure

Over most of the water depth, the speed of the tidal current varies by less than ±25% from the depth-averaged value. Its direction can be assumed to be within ±10° of the direction of the depth-averaged tidal current. For a wide variety of locations the following power law formulae give a good fit to measured tidal current profiles:

\[
\begin{align*}
\bar{u}_{t(z)} &= \left(\frac{z}{0.32h}\right)^{0.32} \bar{u}_t \quad \text{for } 0 \leq z \leq 0.5h \\
\bar{u}_{t(z)} &= 1.07\bar{u}_t \quad \text{for } 0.5h \leq z \leq h
\end{align*}
\]

where \( u_{t(z)} \) = speed of the tidal current at a height \( z \) above the sea bed

\( \bar{u}_t \) = depth-averaged speed of the tidal current

\( z \) = height above the sea bed

\( h \) = total water depth.

Results from using these formulae are usually accurate to within ±15% but they are less accurate very near the sea bed, in deep water and in areas of weak tidal currents. There are also some locations where measurements show that the maximum tidal current may occur at mid depth, e.g. in the Celtic Sea to the south of Eire and near the Brent oilfield.

Where a more accurate tidal current profile is needed in the neighbourhood of the seabed, the following logarithmic formulae are better:

\[
\begin{align*}
\bar{u}_{t(z)} &= \frac{\bar{u}_t \ln(z/z_{ob})}{\ln(\delta/2z_{ob}) - \delta/2h} \quad \text{for } z_{ob} \leq z \leq 0.5\delta \\
\bar{u}_{t(z)} &= \frac{\bar{u}_t \ln(\delta/2z_{ob})}{\ln(\delta/2z_{ob}) - \delta/2h} \quad \text{for } 0.5\delta \leq z \leq h
\end{align*}
\]

where

\( z_{ob} \) = seabed roughness length, determined by the nature of the seabed - see Table 14

\( \delta \) = thickness of the boundary layer - see Figure 8.

c) Storm surge currents - depth-averaged values

Estimates of 50-year return depth-averaged hourly-mean storm surge current are shown in Figure 9. In some areas the currents appear to follow preferred directions, shown by the bold arrows. Where no preferred direction is shown it should be assumed that the extreme storm surge current can occur in any direction.
Contours are in metres.
In the shaded regions, and in coastal regions shallower than 20 m, \( \delta \) should be assumed to be equal to the water depth.
Source: OTH 89 29941.

Figure 8  Boundary-layer thickness, \( \delta \)
Bold arrows indicate the direction of the maximum current in regions where the computed surge currents have preferred directions.
Contours are in m/s.
Dashed line is the 100 fathom (183 m) depth contour.
Source: Numerical model simulations (OTH 89 299)\(^{(4)}\).

Figure 9    Estimates of 50-year return depth-averaged hourly-mean storm surge currents
Table 14  Typical values of seabed roughness length, $z_{ob}$ for different bottom types

<table>
<thead>
<tr>
<th>Bottom type</th>
<th>$z_{ob}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mud</td>
<td>$0.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>Mud / sand</td>
<td>$0.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>Silt / sand</td>
<td>$0.05 \times 10^{-3}$</td>
</tr>
<tr>
<td>Sand (unrippled)</td>
<td>$0.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>Sand (rippled)</td>
<td>$6 \times 10^{-3}$</td>
</tr>
<tr>
<td>Sand / shell</td>
<td>$0.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>Sand / gravel</td>
<td>$0.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>Mud / sand / gravel</td>
<td>$0.3 \times 10^{-3}$</td>
</tr>
<tr>
<td>Gravel</td>
<td>$3 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Source: OTH 89 29d4

d) Storm surge currents - vertical structure

The vertical structure of storm surge currents cannot be estimated with confidence because the relevant physical processes are not yet understood. The bi-linear profile suggested below is certainly an oversimplification and will be changed as understanding increases.

The sea responds to wind forcing with currents on two different scales and the vertical structure of the 50-year return storm surge current at any particular location has contributions from both responses:

- On the small or local scale, the response is wind drift and is confined to a surface layer, at most a few metres thick, in which the current is highly sheared and approximately in the direction of the wind. The current speed at the surface is of the order of 3% of the wind speed and probably decays logarithmically with depth from the surface value.

- On the large scale, sea surface slopes are generated giving storm surges with which currents are associated. Storm surge dynamics are similar to tide dynamics and the profiles given in Section 6.3 b) are appropriate.

OTH 89 29d4 describes an appropriate overall vertical structure if the current profile alone is wanted (without waves) but, in order to apply the wave-current interaction theory of Section 10.3 (where a two-dimensional bi-linear current profile is the most complex that can be accommodated), the following simplified current profile is suggested. It consists of a sloping straight line near the surface to represent the decay of wind drift and a vertical line below to represent the storm surge current:

$$ u_{s(z)} = \bar{u}_s + \frac{(z - h')}{10} \text{ for } h' \leq z \leq h $$

$$ u_{s(z)} = \bar{u}_s \text{ for } 0 \leq z \leq h' $$

where

- $u_{s(z)} = $ speed of storm surge current plus wind drift at a height $z$ above the sea bed (in m/s)
- $u_s = $ depth-averaged storm surge current from Figure 9 (in m/s)
- $z = $ height above the sea bed (in m)
\[ h = \text{total height between the sea bed and still water level (in m)} \]
\[ h' = \text{height above the sea bed at which the current profile changes slope (in m)} = h - 10 \left( u_{w} - \bar{u}_{s} \right) \]
\[ u_{w} = 0.03 \times \text{wind speed from Figure 1 in Section 3.3 (in m/s).} \]

(Note that if \( u_{s} > u_{w} \) the profile is simply:
\[ u_{s(0)} = \bar{u}_{s}, \quad \text{for } 0 \leq z \leq h \])

It is necessary to introduce a multiplying factor throughout the bi-linear profile to ensure that the average current obtained by integrating the profile from the sea surface to the sea bed is equal to the depth-averaged storm surge current. The factor is:
\[
\begin{bmatrix}
1 + 5 \left( \frac{u_{w} - \bar{u}_{s}}{h\bar{u}_{s}} \right)^{2} \end{bmatrix}^{-1}
\]

The modifications necessary to this profile as the sea surface rises and falls due to waves are described in Section 10.3.

e) Tide and surge combined - depth-averaged values

The 50-year return current due to tide and surge cannot be predicted with confidence because very few observations of currents have lasted longer than 1 year. However, by analogy with sea levels for which longer records exist, an estimate may be obtained by adding the extreme surge current of Figure 9 to the spring tidal current of Figure 6. In view of the greater uncertainty involved it is inappropriate to multiply this sum by a factor similar to the \( E_{50} \) used for total still water level. To obtain an estimate of extreme total current, the appropriate values for other residual currents should be added to this sum (see Section 6.3 g)).

Only two sets of current observations have been analysed to predict extreme combined current and the results were within 15% of the indicative values (OTH 89 299). In general, more conservative error bars, of ±25%, are appropriate, particularly near the shelf edge where the spring tidal current is a poor indicator of maximum tidal current.

If directional values are required, the surge current should be assumed to act in any direction unless the site is close to a bold arrow in Figure 9. In this case a conservative estimate is again obtained by making this same assumption but an alternative approach, where the dominant directions of the tidal and surge currents are the same, is to assume that the total current has the same directional properties as the tide. Since the extreme tide-plus-surge current is obtained from the vector sum above, its directional distribution is determined largely by the tidal ellipse, either smeared (if the extreme surge current is taken to be omnidirectional) or identical to it if the surge directional distribution is assumed to be the same as that of the tide.

If the value of the combined current at a different return period is required, this may be obtained by applying the correction factor in Table 10.
f) Tide and surge combined - vertical structure

The vertical structure of extreme current due to tide and storm surge acting together will be the sum of the individual vertical profiles indicated by the methods of Section 6.3 b) and d). To maintain the bi-linear profile of Section 6.3 d), the depth-averaged average spring tidal current should be added to the profile described in Section 6.3 d). In the neighbourhood of the sea bed, a more accurate profile can be obtained by using the logarithmic formulae of Section 6.3 b) but with \( \bar{u} \) replaced by the vector sum of the tidal and storm surge currents.

g) Other residual currents

Estimates of other residual currents should be added vectorially to tide and storm surge to predict total extreme current at a location. Some of the other residuals are very local in effect and most are strongly seasonal (see Section 6.4), so that they may be absent from current measurements made at a location over a short period only. The following notes on other residual currents refer primarily to currents on the UK Continental Shelf; the characteristics of these currents in deeper waters are summarised in Section 6.5.

- **Internal waves** on the Continental Shelf may form where there are large vertical changes in water density, for instance at the interface between a warm near-surface layer caused by heating during the summer and cooler near-bottom water. They can have any period between about 16 hours and a few minutes but frequently are related to the tides, either having a tidal period or comprising packets of internal waves recurring with tidal periods. In the southern Celtic Sea between the shelf edge and 50km shoreward, the resulting horizontal currents have been observed to have near-surface speeds between 0.1 and 0.4m/s and a period of about 30 minutes.

- **Inertial currents** rotate clockwise with a period of about 15 hours and have a constant speed. They occur in summer above the thermocline and are usually initiated by changes in the wind. Speeds of up to 0.2m/s have been observed in the Celtic Sea and the northern North Sea.

- **Currents along fronts.** Fronts are regions of pronounced horizontal density change (due to salinity or temperature differences) and may occur at positions coinciding approximately with the edges of the shaded areas in Figure 8. The speeds of currents along fronts are generally in the range 0.1-0.3m/s near the surface and decrease with depth. Instabilities in the fronts may cause higher speeds in very localised areas. These currents are very localised.

- **Circulation,** or mean flow, is generally less than 0.05m/s but in places can reach 0.15m/s. The largest speeds are usually within a few kilometres of significant changes in topography - headlands, islands, sandbanks. Circulation can vary radically over short distances.

6.4 SEASONAL VARIATIONS (CURRENTS)

There are small monthly and seasonal variations, of the order of ±10%, in spring tidal currents. The largest spring tides tend to occur near the spring and autumn equinoxes.

In the light of present knowledge it is impossible to quantify the seasonal variation of extreme storm surge currents. However, storms and storm surges tend to be more severe in winter as does surface wind drift (see the seasonal variation of wind strength in Table 7 in Section 3).

The residual currents of Section 6.3 g) that depend on the presence of a seasonal thermocline - internal waves, inertial currents and currents along fronts - are all summer and autumn phenomena. At present the
seasonal variation of the circulation cannot be quantified but it is likely to be significant since the forcing 
effects (winds, heat and freshwater input) vary seasonally.

6.5 CURRENTS IN DEEP WATERS

On the basis of present knowledge it is difficult to give indicative values of currents in the deeper waters 
surrounding the UK Continental Shelf. The change from the current regime of the Continental Shelf to the 
regime typical of deep water occurs across the continental slope, which varies in gradient from a smooth 
gradual slope north west of Shetland to a much steeper and more heavily indented slope south west of the 
UK. Currents on the slope are strongly influenced by the local seabed topography and the prevailing 
oceanographic conditions.

In assessing the likely maximum current at a deep water location, measurements of the current throughout 
the water depth should be made and analysed for at least 1 year. However, there are some general comments 
that can be made about currents on the slope:

- **Internal waves** (see Section 6.3 (g)) are more prevalent than in Continental Shelf seas since the water 
column is always stratified. Internal waves with a period of about 30 minutes have been recorded in 
the North West Approaches and may be responsible for measured currents exceeding 1m/s recorded 
near the sea bed in the Faeroe-Shetland Channel at a depth of approximately 500m. There are a 
number of measurements on record of hourly-mean currents in the range 1.2-1.4m/s. Peak currents 
may be even higher since measuring systems with a 1-hour averaging time may well under-estimate 
peak values. Internal waves of tidal frequency may form at the shelf edge where tidal currents cross 
the relatively sharp depth change. Currents from this source may make a significant contribution to 
extreme total currents in the deeper waters of the South Western Approaches.

- A **persistent northward flowing current** has been observed at many locations on the continental 
slope around the UK. Its speed is greater than 0.5m/s in places and it appears strongest on the upper 
slope, i.e. in water depths around 500m. In the Faeroe-Shetland Channel, this current is underlain by 
cold water flowing to the south west, causing strong vertical shear between the two water masses.

- **The Norwegian Coastal Current** is a persistent flow of less saline surface water away from the 
Skagerrak along the line of the Norwegian Trench and northward along the coast of Norway. Its 
width and speed vary with location and time of year. Mean speeds are in the range 0.1-0.3m/s, 
although instabilities in the front separating it from North Sea waters may propagate as gyres (or 
whirls) with surface current speeds exceeding 1.5m/s.

- **Meteorological events** can induce large changes in flows over the continental slope.

- **The tidal component** of total current is relatively less important on the continental slope. The speed 
of the maximum tidal current generally decreases with distance from the shore, in inverse proportion 
to the water depth. Stratification of the water column in deep water may cause significant variations 
in the vertical structure of the tidal current.
7. AIR AND SEA TEMPERATURES

7.1 INTRODUCTION

Extreme temperatures have been estimated in the past as ‘probable extremes’, i.e. the values probably never exceeded, and not ‘extreme values with a specified return period’. This practice is continued here. Comparisons show that probable extremes at the sea surface are sometimes more extreme than corresponding 50-year return temperatures, but not by more than 2°C (OTH 89 299)\(^{(4)}\).

Minimum temperatures on land are generally lower than minimum temperatures at sea, and the lowest temperature experienced by an offshore installation may possibly occur during fabrication.

The lowest observed daily-mean air temperature (LODMAT) is of interest for applications where structures respond only slowly to changes in the air temperature.

‘Wind chill’ affects the rate of heat loss from a body maintained at a temperature higher than its surroundings. It is thus inappropriate to make wind chill corrections to temperatures when designing structural members of offshore installations, although it may sometimes be appropriate to do so in the design of heating and process plant.

7.2 SITE-SPECIFIC MEASUREMENTS (TEMPERATURES)

a) Surface temperatures

Estimates of extreme air temperatures derived from site-specific measurements at a location should not be used in preference to the indicative values of Section 7.3 a) unless at least 10 years of daily maximum and minimum temperature measurements are available at the location for analysis. Shorter periods of measurement may coincide with relatively mild conditions only. It is also unlikely that a short series of measurements can be calibrated against a series extending over 10 or more years at a climatologically similar neighbouring site - because of the scarcity of fixed offshore sites where long sets of temperature measurements have been recorded.

The probable extreme air temperature at a location may be estimated from the 10-year series of daily measurements by extracting the lowest and highest temperatures from the record. These extremes should be examined and verified in the context of the complete temperature distribution and the other weather conditions at the time of occurrence.

Extremes of sea surface temperature occur less frequently than air temperature extremes, and it is unlikely that estimates of probable extremes derived from site-specific measurements will be more accurate than the indicative values of Section 7.3 a).

b) Sea temperatures - vertical profile

Because it is particularly difficult to establish indicative values of the profiles of extreme temperatures throughout the water depth (see Section 7.3 b)), maximum use should be made of whatever site-specific measurements have been made:
if 5 or more years of temperature measurements throughout the water depth are available, they should be used to adapt the general mean profile recommended in Section 7.3 b) so that it represents the specific location of the installation more closely

a much longer series of measurements (long enough to establish the local sea climatology) would be necessary to establish site-specific profiles of extreme temperatures at the location

where no temperature measurements at all are available, at least the measured water depth at the location should be used in conjunction with the generalised profiles recommended in Section 7.3 b) in order to estimate extreme temperatures on the sea bed.

7.3 INDICATIVE VALUES (TEMPERATURES)

a) Surface temperatures

Estimates of probable extreme maximum and minimum temperatures, in the air and at the surface of the sea, are shown in Figures 10 to 13. The sea and air temperatures are applicable to deep water offshore locations only.

The contours cannot be more accurate than ±1°C and errors are likely to be greater in data-sparse areas, i.e. to the west of Ireland and the west and north of Scotland.

Figure 14 shows estimates of lowest observed daily-mean air temperatures, LODMAT. They have been derived from the extreme minimum air temperature data (see Figure 11) using conversion factors based on the detailed temperature data available at fixed offshore weather stations. The contours therefore follow the same pattern as those in Figure 11, but the temperatures are generally a degree or two higher except around the -4°C and -6°C contours.

For use of these values in calculations relating to extreme loading, see Section 10.4.

b) Seabed temperatures and vertical profile

Probable extreme minimum seabed temperatures are likely to be close to extreme minimum sea surface temperatures in the southern North Sea, the English Channel and the Irish Sea because the waters in these areas have almost no vertical temperature gradient in winter.

In the summer, there is often a very marked thermocline in all UK waters (except those shallower than about 25m). Probable extreme maximum seabed temperatures are therefore less than surface extreme maxima.

It is not feasible to produce contoured maps of estimates of indicative values of probable extreme maximum and minimum seabed temperatures. The values are closely dependent on water depth, and water depth may vary markedly over quite short horizontal distances. If no measurements are available at a location on which to base site-specific estimates, probable extremes may be calculated from the temperature profiles published by the US Navy in 1967, or from other sources (e.g. Tomczak and Goedecke 1967 or MAFF 1981). US Navy 1967 gives profiles for the months of February, May, August and November - mean profiles and the range of observed temperatures at all depths. Representative profiles are available for sea areas in the North Atlantic and surrounding waters.
Contours are in °C.
Source: Examination of data from VOF ships and fixed offshore weather stations (OTH 89 299).
Contours are in °C.
Source: Examination of data from VOF ships and fixed offshore weather stations (OTH 89 299(4)).

Figure 11 Estimates of probable extreme minimum air temperatures over the sea
Contours are in °C.
Source: Examination of data from VOF ships and fixed offshore weather stations (OTH 89 299).

Figure 12 Estimates of probable extreme maximum sea surface temperatures
Contours are in °C.
Source: Examination of data from VOF ships and fixed offshore weather stations (OTH 89 299(4)).

Figure 13 Estimates of probable extreme minimum sea surface temperatures
Contours are in °C.
Source: Figure 11 data combined with an analysis of measured data from fixed offshore weather stations\textsuperscript{(4)}.

Figure 14  Lowest observed daily-mean air temperatures
8. SNOW AND ICE

8.1 INTRODUCTION

Estimates should be made of the extent to which snow and ice may accumulate on an offshore installation. Information on the maximum permitted accumulations, together with details of the action to be taken if the accumulations appear likely to exceed the permitted levels should be available to personnel on the installation.

8.2 INDICATIVE VALUES (SNOW AND ICE)

Because of the lack of reliable relevant climatological data and calibrated modelling techniques it is impossible to make accurate predictions of likely accumulations of snow and ice on offshore installations. Build-up of ice and/or snow are such rare events that maximum accumulations with return periods of 50 years are very difficult to predict; the recommendations and values given below and in the summary Table 15 are based on conservative assumptions.

a) Snow

Accumulations of snow are more likely to occur than icing.

Snow may settle on non-horizontal windward-facing parts of an installation if the snow is sufficiently wet. On vertical surfaces it is only likely to stay in position as snow for a few hours although it may then freeze and remain as ice (see Section b) below). The likely maximum thickness of snow on vertical surfaces is estimated to be 40mm for locations throughout the North Sea - see Table 15. It will affect all exposed elements above the splash/spray zone and should be assumed to adhere to half the circumference of each element.

Corresponding thicknesses of wet snow on exposed horizontal surfaces above the splash zone are also shown in Table 15; dry snow will be blown off as soon as any thickness accumulates. Wet snow on horizontal surfaces may remain in position for some time.

For use of these values in calculations relating to extreme loading, see Section 10.5.

b) Ice

Ice may form on an offshore installation through four natural mechanisms:

- freezing sea spray
- freezing of old wet snow
- freezing fog and supercooled cloud droplets
- freezing rain.

On a 50-year return period criterion, there is no reason to believe that icing from freezing fog, supercooled cloud droplets or freezing rain is of any significance in UK designated waters.
The combination of conditions necessary for icing from freezing sea spray have occurred only very rarely in the North Sea other than near the Dutch coast. Because of the rarity it is not possible to estimate 50-year return thicknesses in UK waters. Estimates of the likely maximum thicknesses calculated from available climatological data are given in Table 15 for the structural member that will be affected, those in the spray zone above the splash zone.

At higher levels, any icing on an installation will be overlain with further accumulations of fresh wet snow.

c) **Sea ice and icebergs**

There is no evidence to suggest that sea and icebergs need to be considered in the design or certification of offshore installations for UK designated waters.
<table>
<thead>
<tr>
<th>Structural element</th>
<th>Wet snow</th>
<th>Ice from freezing sea spray</th>
<th>Ice from frozen snow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thickness (mm)</td>
<td>Density (kg/m³)</td>
<td>Thickness (mm)</td>
</tr>
<tr>
<td><strong>At latitude 52°N</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tubular member below deck level</td>
<td>-</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Tubular member below deck level *</td>
<td>40</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Lattice member above deck level</td>
<td>40</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Horizontal surface</td>
<td>150</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td><strong>At latitude 54°N</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tubular member below deck level</td>
<td>-</td>
<td>-</td>
<td>15</td>
</tr>
<tr>
<td>Tubular member below deck level *</td>
<td>40</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Lattice member above deck level</td>
<td>40</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Horizontal surface</td>
<td>240</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td><strong>At latitude 57.7°N</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tubular member below deck level</td>
<td>-</td>
<td>-</td>
<td>25</td>
</tr>
<tr>
<td>Tubular member below deck level *</td>
<td>40</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Lattice member above deck level</td>
<td>40</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Horizontal surface</td>
<td>200</td>
<td>100</td>
<td>-</td>
</tr>
</tbody>
</table>

The values in the table have been predicted from a model covering North Sea waters west of 3° E. There is no available data for other UK designated waters but it is suggested that the values in the table may also be used for comparable latitudes west of the UK mainland. The thickness relates to increase in radius in relation to tubular members.

* Icing on members below deck level from freezing sea spray is likely to start about 4-7m above MSL at the thickness indicated and reduce to zero thickness at a height of about 9-15m above MSL.

* Snow and ice from freezing of old wet snow will accumulate on members below deck level only above the splash/spray zone.

# Because of the absence of data no estimates can be made of the depth of accumulations north of 57.5°N. However, the values for 57.5°N are sufficiently conservative to be used for UK designated waters north of this latitude.

Source: Theoretical calculations based on climatological data (OTH 89 299)
9. MARINE GROWTHS

9.1 INTRODUCTION

All installations in UK designated waters are likely to become fouled with growths of marine organisms. The growths may affect wave loading on structural members and the need for cleaning prior to underwater structural inspections. Wave loading is increased because of the extra diameter of the members affected and because of the extra roughness of the member surface.

Permitted levels of growth should be available to personnel on the installation and growths should be removed as necessary to ensure that these levels are not exceeded.

9.2 INDICATIVE VALUES (MARINE GROWTHS)

Growths are likely to extend from the splash zone to the sea bed with the greatest thicknesses between the spring tidal level and -40m from the mean sea level datum. Typical growth characteristics of some of the more common fouling species are detailed in Table 16. Growth rates of most species are greater in summer than winter and colonies of some species (e.g. weeds and mussels) may occasionally be reduced by wave action during the winter months.

An initial forecast of growth rates and likely overall thicknesses at a location should be made before the design of an installation is finalised. The forecast should be made by a person competent and experienced in such matters, drawing on his general experience supplemented by experience of growth rates at any nearby sites and likely sources of seeding. It can be assumed that this forecast will be superseded within 2 years, when sufficient underwater visual inspections will have been carried out to enable a site-specific forecast to be made of continuing growth rates.

Significant fouling may be expected at any site within 2 years of installation and some cleaning is usually required after about 4 years. After cleaning, the installation may not necessarily be re-colonised with the same species.

When fouling inspection reports are available (see OTH 89 299(4) for details of the content of the reports), site-specific forecasts can be made of likely marine growths. The forecasts should cover individual growth rates of the principal species on the installation, the overall rate of thickness increase and likely terminal thickness. The need for further inspections and cleaning action should be based on the results of these forecasts.
Table 16  Growth characteristics of common marine fouling species

<table>
<thead>
<tr>
<th>Type</th>
<th>Settlement season</th>
<th>Typical growth rates</th>
<th>Typical coverage (%)</th>
<th>Typical terminal thickness</th>
<th>Depth range (relative to MSL)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hard fouling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mussels</td>
<td>July to October</td>
<td>25 mm in 1 year</td>
<td>100%</td>
<td>150 to 200 mm</td>
<td>0 to 30 m</td>
<td>But faster growth rates are found on installations in the southern North Sea</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50 mm in 3 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>75 mm in 7 years</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solitary tubeworms</td>
<td>May to August</td>
<td>30 mm (in length) in 3 months</td>
<td>50-70%</td>
<td>About 10 mm (tubeworms lay flat on the steel surface)</td>
<td>0 to mudline</td>
<td>Coverage is often 100%, especially on new structures 1 to 2 years after installation. Tubeworms also remain as a hard, background layer when dead</td>
</tr>
<tr>
<td><strong>Soft fouling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydroids</td>
<td>April to October</td>
<td>50 mm in 3 months</td>
<td>100%</td>
<td>Summer: 30 to 70 mm</td>
<td>0 to mudline</td>
<td>A permanent hydroid ‘turf’ may cover an installation and obscure the surface for many years</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Winter: 20 to 30 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plumose anemone</td>
<td>June to July</td>
<td>50 mm in 1 year</td>
<td>100%</td>
<td>300 mm</td>
<td>-30 m to -120 m (0 to -45 m on platforms in southern North Sea)</td>
<td>Usually settle 4 to 5 years after installation and can then cover surface very rapidly. Live for up to 50 years</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-30 m to -120 m (0 to -45 m on platforms in southern North Sea)</td>
<td></td>
</tr>
<tr>
<td>Soft coral</td>
<td>January to March</td>
<td>50 mm in 1 year</td>
<td>100%</td>
<td>About 200 mm</td>
<td>-30 m to -120 m (0 to -45 m on platforms in southern North Sea)</td>
<td>Often found in association with anemones</td>
</tr>
<tr>
<td>Seaweed fouling</td>
<td>February to April</td>
<td>2 m in 3 years</td>
<td>60-80%</td>
<td>Variable, but up to 3 m</td>
<td>-3 m to -15 m</td>
<td>May be several years before colonisation begins but tenacious holdfast when established. Present on some installations in northern and central North Sea</td>
</tr>
<tr>
<td>Kelp</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
10. COMBINATIONS OF EXTREME PARAMETERS

10.1 INTRODUCTION

It is unlikely that extreme values of all individual metocean parameters (wave, current, wind, etc) will occur simultaneously and produce the worst possible structural effect. Allowance may therefore be made for the reduced probability of two or more uncorrelated or partially correlated parameters acting together (OTH 89 299).4]

However, in making such allowance, due account should be taken of any reduction in those safety factors which are otherwise implicit in designs in which it is assumed that extreme values with a 50-year return period occur simultaneously, which tend to compensate for the fact that individual values with a 50-year return period have a significant probability of occurrence in any year (0.02). Thus, if account is taken of joint probabilities, then unless safety factors elsewhere in the design process are adequate, consideration should be given to the use of individual values with a longer return period than 50 years, together with appropriate joint probability factors. Such factors should be based on adequate information about the joint probabilities of extreme events. Account should also be taken of any uncertainties (e.g. likely errors or methodological uncertainties) in measuring or estimating the individual parameters.

The combinations of parameters which are liable to arise in the design process may be quite specific to the structural element under consideration (see also Section 1.2). However, there are many cases where the combination required is one of a few standard types, and this section makes recommendations on the appropriate procedures for such cases. The standard types considered are:

- combinations of water depth, tidal and surge elevation and wave crest height, e.g. for use in ‘air gap’ calculations
- combinations of extreme wave and current velocities, for use in extreme force calculations
- combinations of snow and ice accumulation and wind speed
- combinations of maximum and minimum temperatures with wind speed and wave height.

10.2 EXTREME SURFACE ELEVATION

The extreme surface elevation is required by designers for various purposes, e.g. to determine the highest level in the structure at which extreme wave and current loads will act or to determine the lowest level at which vulnerable elements of superstructure may be placed. A particularly important application is to determine the level at which the base of the topside structure should be set, in view of the fact that the horizontal wave and current loads on the structure increase very rapidly if there is any contact between the wave crest and the topside structure (see also OTO 2001 013).

In the absence of any allowance for the joint probabilities of occurrence of extreme waves and extreme still water level variations, the value of the extreme surface elevation with a 50-year return period (E₅₀) would be given by:

\[ E_{50} = d_m + L_{50} + C_{50} \]
where
\[d_m\] = the mean water depth
\[L_{50}\] = the 50-year extreme still water level variation (with respect to the mean sea level) due to tidal and surge variations
\[C_{50}\] = the 50-year extreme wave crest elevation.

The \(N\)-year return value (again with no allowance for the joint probabilities of extreme wave and still water variations) can be written in the form:
\[E_N = d_m + L_{50} F_N + C_{50} G_N\]

where
\[F_N = \frac{L_N}{L_{50}}\]
\[G_N = \frac{C_N}{C_{50}}\]

The best available estimate for \(F_N\) (see Section 5.3 d)) is:
\[F_N = 0.89 (1 + 0.03 \ln N)\]

The value of \(G_N\) can be inferred from Section 4.2 b) as:
\[G_N = 0.72 (1 + 0.1 \ln N)\]

If relevant information on joint probabilities is available (and it should be noted that the information has to relate to the joint probabilities of extreme events - it should not be assumed that these are closely similar to the joint probabilities of non-extreme events) the expression for \(E_N\) above can be replaced by:
\[E_N = d_m + L_{50} F_N P + C_{50} G_N\]

where \(P\) is a suitably chosen joint probability factor which is more fully discussed in OTH 89 299\(^{4}\). A value of \(P\) less than unity should only be used to the extent that the uncertainties in the values of \(d_m, L_{50}\) and \(C_{50}\) are such that overall structural safety is not jeopardised.

10.3 EXTREME FLUID VELOCITY

The extreme water particle velocity incident on an installation, required to estimate extreme loading on the structure, is calculated by combining in an appropriate manner the extreme current velocity with the water particle velocity due to the extreme wave. In the deterministic design procedure, the extreme fluid velocity is appropriately calculated on the assumption that a periodic two-dimensional wave with crest-to-trough height \(H_N\) (as defined and specified in Sections 4.2 b) and 4.3 b)) and an associated period \(T_{ass}\) (as defined and specified in Section 4.2 c)) is travelling on a unidirectional sheared current with a profile as set out in Section 6.3 f).

One justifiable procedure for calculating the extreme fluid velocity is:

1. The extreme depth-averaged tide and surge currents should be determined by the procedures set out in Sections 6.3 a) and c). The directions of these currents should be assumed to be co-linear with the direction of the extreme wave, and they should have the same return period as the wave. No
joint probability factors should be applied unless the designer has adequate and relevant information as discussed in Section 10.1.

2. The inflection point, and the mean slope of the ‘formal current profile’ above and below this point, should be determined on the basis of the considerations set out in Sections 6.3 d) and f). The formal current profile is the current profile that would exist in the absence of any wave.

3. Using this formal current, a suitable wave-current interaction theory should be used to calculate the total fluid velocity profile (see OTH 89 299)\(^4\).

An acceptable, although less accurate, alternative to Stage 3 above is to stretch the formal current up to the wave crest by multiplying \(z, h\) and \(h'\) (see Section 6.3 d)) by the factor \((1 + C_N/d_m)\) where \(C_N\) is the wave crest elevation obtained from a suitable non-linear wave theory which takes no account of the current (e.g. Stokes 5th order or Dean’s theory) without attempting to alter the depth-averaged current so as to conserve total mass flow, and then to add the velocity derived from the wave theory. (\(C_N\) is not necessarily the same as in Section 4.2 b.) At points on the wave profile other than the wave crest, \(C_N\) should be replaced by the wave surface elevation relative to the still water level.

### 10.4 EXTREME TEMPERATURES COMBINED WITH EXTREME WIND SPEED AND WAVE HEIGHT

Analysis of metocean observations from the ships of the voluntary observing fleet in the waters around the UK has shown that extreme temperature conditions are associated with extreme wind speeds and extreme wave heights having return periods of less than 50 years (OTH 89 299)\(^4\).

It is recommended that when assessing the effects of the probable extreme maximum and minimum air temperatures of Section 7.3 it can be assumed that the wind speed and wave height accompanying them will not exceed the values with a 5-year return period.

### 10.5 EXTREME SNOW AND ICE COMBINED WITH EXTREME WIND SPEED

Measurements at light vessels and offshore weather stations in the North Sea have shown that 50-year return ice and snow accumulations are associated with extreme wind speeds having return periods less than 50 years (OTH 89 299)\(^4\).

In the North Sea at latitudes less than 57.5°N, it is recommended that when assessing the structural effects of the 50-year return snow and ice accumulations of Section 8.2 the wind speed and wave height accompanying them will not exceed the 2 or 5 -year return wind speeds from Section 3.3, i.e. wind speeds of between 75% and 83% of the 50-year return wind speed. The lower end of the range is appropriate for areas near the UK coast and the higher end to the continental coast. In all areas of the North Sea above 57.5°N it is likely that the associated wind speed will be at the top end of the range, i.e. the 5 -year return wind speed.

These reduction factors are not necessarily applicable to UK waters other than the North Sea.
11. METOCEAN PARAMETERS FOR FATIGUE CALCULATIONS

11.1 INTRODUCTION

Methods of carrying out a fatigue analysis of an offshore installation and the form of metocean data required for each method are described in Offshore Technology Report OTO 2001 013. Metocean parameters are required describing wave or sea state heights, wave lengths, periods and direction, current speed and directions, sea level and (if they are likely to cause significant stress ranges) wind speeds.

11.2 WAVE PARAMETERS

Wave data which may need to be derived include:

- cumulative frequency distributions (i.e. exceedance diagrams) of the heights of all individual zero-up-crossing waves likely to be encountered during a year, either as an omnidirectional data set or for each of a number of representative directions, together with representative wave periods for the waves of different heights
- scatter diagrams (i.e. bivariate probability distributions) of individual wave heights and periods for each representative direction throughout a year
- scatter diagrams of sea-state occurrence for each representative direction together with the appropriate wave spectrum for each sea state.

a) Cumulative frequency distributions

Wherever possible, the cumulative frequency distribution of individual wave heights should be derived from a sea state scatter diagram (significant wave height, \( H_s \); mean zero-up-crossing period, \( T_z \)) which has been obtained from data measured at the location of the installation. The sea state scatter diagram should be based on site-specific measurements obtained over a period of at least 1 year.

The individual wave height distribution may be determined either by assuming an exponential distribution of the cumulative number of wave exceedences as a function of wave height, the highest wave in a year and the total number of waves being determined from the scatter diagram, or by the technique described by Battjes 1970\(^{18}\).

If there are insufficient data (less than 1 year), then for fatigue calculations it may be assumed that the frequency distribution is a negative exponential distribution of the form:

\[
h = D (\ln N_y - \ln N_h)
\]

where

- \( h \) = wave height
- \( N_h \) = the number of waves exceeding \( h \) in a year
- \( D \) = the distribution parameter, with value depending upon the location
- \( N_y \) = the total number of zero-up-crossing waves expected at the location in a year.

Values for \( D \) and \( N_y \) may be estimated from a consideration of those derived from data from nearby sites, shown in Figure 15.
The first number at each location is Ny (10^8).
The second number at each location is D (m).
Source: Analysis of measurements (OTH 89 300).^{5}

Figure 15 Estimates of N_y (number of waves per year) and D (distribution parameter) at sites where sufficient measurements are available.
b) Directional individual wave height distributions

The directional distribution of the sea state may be derived from the (1-year) $H_s:T_z$ scatter diagram and knowledge of the wind direction at the time of measurement. Assuming that wave direction corresponded with wind direction at the time of measurement, directional scatter diagrams can be constructed from which the number of waves in each direction can be calculated using either the exponential or Battjes’ methods (18).

The sea state scatter diagrams should be based on site-specific measurements of sea states obtained over a period of at least 1 year. If these are not available, indicative sea state scatter diagrams may be obtained for a location by adapting the measured diagrams from a nearby site using some suitable scaling procedure that ensures the correct directional values of $H_{50}$ (see Section 4.2 b)) for the location. See MIAS 1985(6) for available scatter diagrams.

In the absence of a site-specific scatter diagram, an alternative approach is to assume that the percentage frequency of waves by direction is proportional to the percentage frequency of winds by direction. Calculate the number of waves per year, by direction, and determine the directional individual wave distribution from the appropriate annual values using the exponential method. This method inevitably implies that the average value of $T_z$ is the same for all directions and is thus subject to greater errors than the scatter diagram approach.

c) Associated periods of individual waves

The method usually employed at present for estimating wave period $T$ to associate with a specified individual wave height $H$ is to assume that $T$ is proportional to $H^{1/2}$. Various simple methods for estimating the constant of proportionality indicate a value of about 4. This approach is not wholly satisfactory, if only because the sum of all wave periods during a year does not add up to a year or - if constrained to do so by increasing the constant of proportionality - the steepness of the waves appears to be far too low.

An analysis of the distribution of period given individual wave height during a year, analogous to Battjes’ analysis (18) of wave height and using results in Longuet-Higgins 1963(12) for the distribution of $H$ and $T$ given $H$, and $T_z$, shows a wide distribution of $T$, given $H$. This indicates a significant probability of waves with large $T$ and explains why the wave periods from the usual method do not add up to a year. The analysis requires a value for the bandwidth parameter $v$ to be specified; the choice for $v$ appears to have relatively small effect upon the results.

If a single value for $T$ is required for the specified $H$ then the modal value, $\hat{T}$ might be used (OTH 89 300)(5); but the relationship between $\hat{T}$ and $H$ depends upon the location. If this relationship is used then the implications upon fatigue analysis of ignoring the spread in values of $T$ given $H$ should be considered.

d) Wave spectra

Measured spectra should be used if they are available, but the spectrum associated with each sea state is normally assumed to be either the generalised Pierson-Moskowitz spectrum (8), or the JONSWAP spectrum (9) whichever is appropriate (see Section 4.1).
11.3 CURRENT PARAMETERS

For deterministic fatigue calculations, the cumulative frequency distribution for the range of variation (over one wave period) of $V$ and $|V|$ is required, where $V$ is the total fluid velocity in a specified direction and at a specified depth due to the combination of waves and currents. With adequate precision, these frequency distributions can be obtained from the frequency distribution of wave heights described in Section 11.2 b). In calculating the range of $V |V|$ it may be necessary to take into account the presence of the current - if its magnitude is comparable with the wave orbital velocity for those waves which make the greatest contribution to fatigue damage (refer to OTO 2001 013 for further information).

11.4 WIND PARAMETERS

Wind parameters to be used in fatigue analyses may be obtained from BS 8100(7) but care is needed when adapting the land-based data of this publication for offshore use.
12. REFERENCES


6. Marine Information Advisory Service. MIAS Catalogue of Wave Data, 1985. [Still exists and has not been updated. Information overtaken by technological developments – now available electronically as BODC Inventory – BODC – British Oceanographic Data Centre (www.bodc.ac.uk) lists locations for which instrumentally recorded wave data are available].


