NEARSHORE WAVE CLIMATE OF THE ENGLISH CHANNEL – EVIDENCE FOR BI-MODAL SEAS

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Bi-modal sea conditions were identified at all measured wave sites along the English Channel. Bi-modal seas were most prevalent at, but not confined to, sites exposed to Atlantic swell. Atlantic swell waves rarely propagate the full length of the English Channel to the Straits of Dover. The swell component may be responsible for crest cut-back on beaches and coastal flooding, which is not predicted by conventional operational procedures. The significance of incorporating swell energy for scheme design along the English Channel coast should be considered.

INTRODUCTION

Measurements of nearshore wave conditions in water depths of less than 12m have been relatively rare, historically, in UK waters. A long-standing outer ring of UK Met Office buoys has been in operation on the continental shelf, in around 50m or more water depth, with the recent addition of some buoys in about 30m, operated by WaveNet, but leaving a dearth of validated wave data nearshore, where the waves undergo most of the transformation of their properties. Accordingly, the Strategic Regional Coastal Monitoring Programmes of Southeast and Southwest England have deployed a network of nearshore wave buoys, to provide a long-term, coastal wave climate for coastal engineering design and to compare beach performance against design conditions.

The rationale of selecting measurement locations is for sites where either high expenditure is needed for beach management schemes for protection against coastal erosion or flooding, or where the wave climate is difficult to model nearshore due to irregular bathymetry or complex patterns of diffraction and refraction, for example in the lee of Portland Bill. The Coastal Wave Network is, therefore, ideally placed to assess the magnitude and the frequency of occurrence of combinations of sea and swell across some 2000km of coastline.

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BACKGROUND

Two factors which prompted an assessment of measured wave climate in the nearshore region are that, firstly, cut-back of beach crests and/or coastal flooding has been observed when conventional formulae would not predict overtopping; and secondly, design criteria for coastal structures typically assume uni-modal conditions characterised by significant wave height, H_s, and mean wave period, T_m, with no account taken of the presence of swell waves. Examples of analytical design equations using H_s and T_m are beach profile models (Powell, 1990) and barrier breaching models (Bradbury, 2000).

For design purposes, the central and especially the eastern parts of the English Channel modelled as a narrow-banded JONSWAP spectrum. Measured data from the Coastal Wave Network has demonstrated that the well-known relationship of $T_p = 1.2T_z$ is regularly exceeded, suggesting that the ambient waves conditions are dissimilar to those modelled by a JONSWAP spectrum.

Following a series of laboratory experiments, Coates *et al.* (1998) suggested that the presence of more than 10% swell energy may be significant for beach management and design criteria. Tests with 20% swell, even if concealed within severe sea conditions, produced overtopping rates twice as high as equivalent tests with no swell. As a result, the presence of 20-50% swell is likely to be important for design conditions, particularly for coastal structures where waves are depth-limited near the toe, since an increase in wave height further offshore would have little additional effect.

Further interest in the swell component of the sea state resulted from the new generation of spectral wave models, such as SWAN; although SWAN does not inherently require sea and swell components to be described separately, since the whole spectrum is incorporated into the wave modelling, modern data assimilation techniques involve wind field parameters to improve wave estimates, so that sea and swell must be treated separately, as only the sea depends on the local wind field (Alkyon, 1999).

The Coastal Wave Network provides an opportunity to assess the extent of swell both spatially and temporally, along a stretch of coastline of about 2000km. The network consists of 20 wave buoys deployed in 10-12m CD water depth along the English Channel and Bristol Channel coastline. The first 6 buoys were deployed in 2003, with the bulk of the remaining buoys becoming operational in 2006. The buoys are Datawell Directional Waverider Mk III, which send real-time, half-hourly wave parameters to the Programmes' website www.channelcoast.org. The buoys measure for 30 minutes at 3.84Hz, but transmit at a reduced sampling frequency of 1.28Hz to the shore station, where the wave parameters are calculated. Since all the buoys can therefore be considered as synchronous, a swell train can be tracked progressing up the Channel in near real-time. Although directional spectra are also measured by the buoys, this research is concerned only with bi-modality in the frequency domain.

METHODS

Definition of a bi-modal sea

A bi-modal sea is described traditionally as having distinct sea and swell peaks, of which a classic example is shown in Figure 1, but complex seas, such as shown in Figure 2 are less straightforward to define.

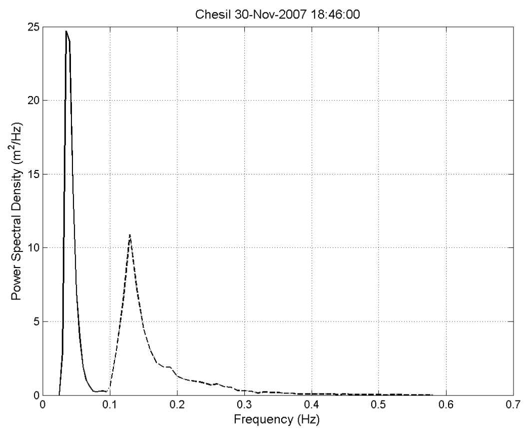


Figure 1. 1-D spectrum from a Directional Waverider in ~12m water depth off Chesil Beach. Total Hs = 3.84m, 44% of the energy is in a well-defined, narrow, low frequency component.

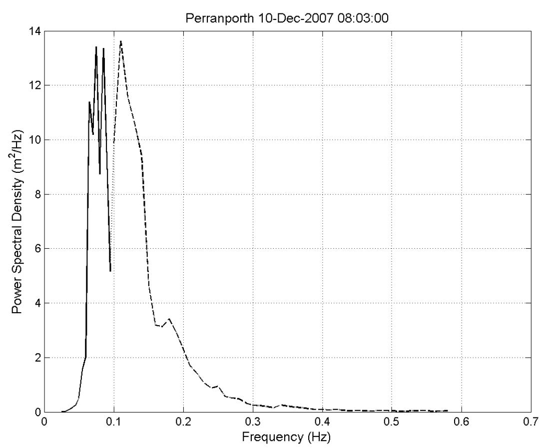


Figure 2. Complex (bi-modal) spectrum

The UK Met Office divides its modelled wave predictions into high frequency (sea) and low frequency (swell) components on the basis of the predicted wind field and, therefore, has a variable separation frequency. In other cases, a fixed separation frequency of 0.1Hz (10s) can be used, classing all wave energy below that as swell. The Waveriders do not measure winds, but since they produce a measured wave spectrum, criteria are needed to split the total spectrum into low and high frequency components based, ideally, around the measured energy trough between the two components (Alkyon, 1999).

Since our interest in the occurrence of bi-modal sea conditions is from an engineering standpoint, it is important that the statistics should concentrate on those seas which may be of importance for the coastal engineer *i.e.* capable of transporting sediment. Accordingly, criteria were derived to select wave spectra which have a well-defined spectral peak in both the sea and swell factions, together with an amount of energy in both components to be of potential significance for sediment transport. The criteria are based on industry-standard Datawell directional Waverider spectra, using 64 spectral frequencies ranging from 40 to 1.7s, with 33 spectral bands between 33 and 3s. The following conditions must all be fulfilled for a sea state to be considered bi-modal:

- Minimum total energy of the wave spectrum is the equivalent of H_s = 0.5m.
- The peak energy in the smaller peak is at least one-third that of the larger peak.
- The peak energy in the smaller peak is at least $0.4m^2Hz^{-1}$ (equivalent of Hs ~ 0.2m at 10s)
- The energy at the trough is less than half that of the smaller peak.

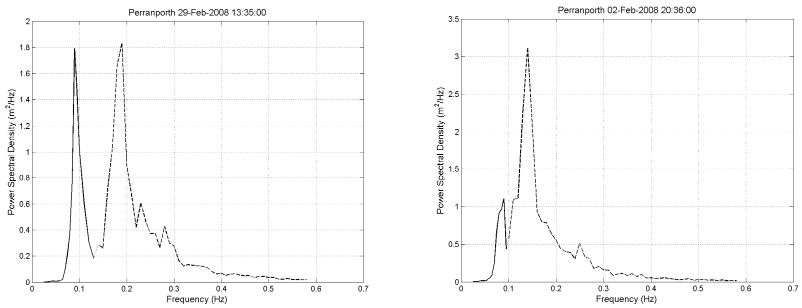
Similar principles have been applied to measured wave spectra from the North Sea, with the addition of smoothing of the edges of each component (Alkyon, 1999).

Bi-modal Events

Although an assessment of the incidence of swell energy is needed to derive the nearshore wave climate of the English Channel, operational beach managers require identification of those periods which may affect beach performance in the short-term. Accordingly, a “Bi-modal Event” is defined where bi-modal seas are present *and* the total H_s is 1.5m or higher *and* where such conditions are continuous for 1 hour or more. This is because beaches, particularly the shingle beaches prevalent along the central and eastern English Channel, can undergo significant modification in this time.

RESULTS

Incidence of bi-modal sea conditions



Off the west coast of Cornwall, with full exposure to prevailing south-westerly winds, many cases of the classic low frequency-dominant spectrum were observed (similar to Figure 1), but occurrences of high frequency dominant conditions were regularly experienced, as well as with similar energy in the sea and swell components (Figure 3).

Figure 3. Bi-modal sea conditions, site fully exposed to Atlantic swell

Analysis found that bi-modal conditions can persist into areas generally more sheltered from the Atlantic swell, including Start Bay and Minehead, as shown in Figure 4, which gives the annual average occurrence of bi-modal sea conditions. The majority of the occurrences are during the winter months, when exposed sites such as Perranporth can experience around 20% bi-modal sea conditions. Hayling Island, in particular, might be expected to receive some shelter from the full Atlantic seas, being in the lee of the Isle of Wight, but nevertheless, experiences between 10 - 25% bi-modal sea conditions during the winter months (Figure 5).

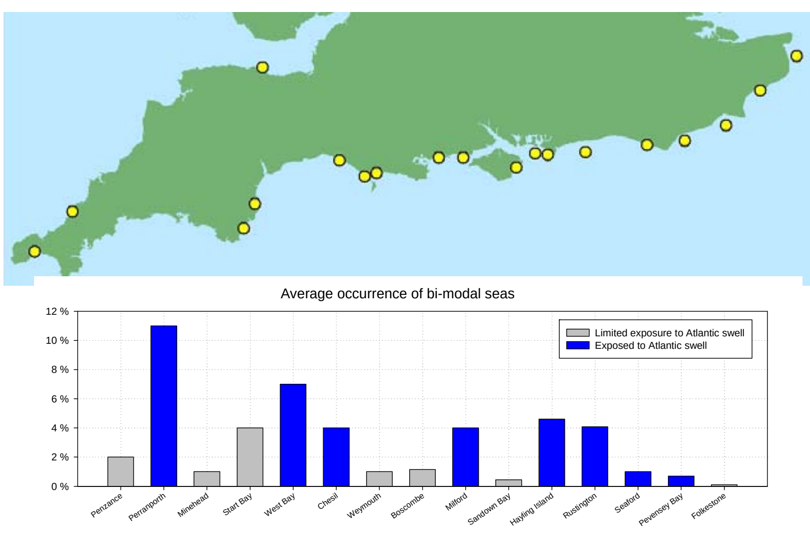


Figure 4. Average annual percentage of bi-modal seas.

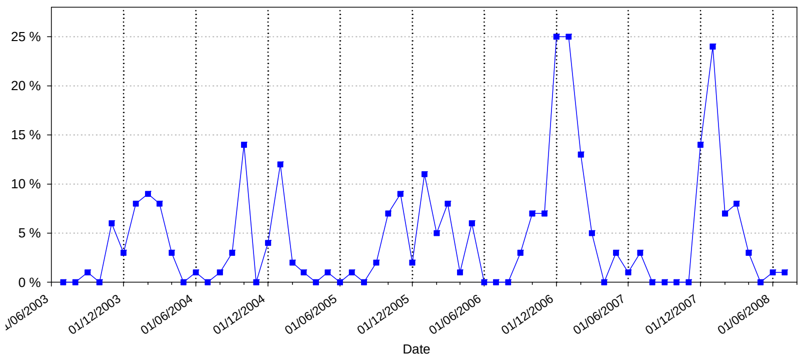


Figure 5. Inter-annual variability of bi-modal seas at Hayling Island

Exposed sites along the central English Channel received broadly similar proportions of bi-modal seas, whilst the most easterly sites averaged only about 1% bi-modal conditions - about the same as the sheltered sites in the western Channel. This suggests that Atlantic swell rarely propagates to the Dover Straits. Nonetheless, as will be shown in the following section, the percentage of occurrence of bi-modal seas is a not necessarily an indicator of their impact on the adjacent beaches.

Occurrence of bi-modal events

Bi-modal sea conditions of significance for operational coastal management were found to occur regularly at most sites along the English Channel, as shown in the example for January 2007 (Figure 6). Many of the adjacent beaches have defined Beach Management Plans, where the beach response to these conditions can be assessed.

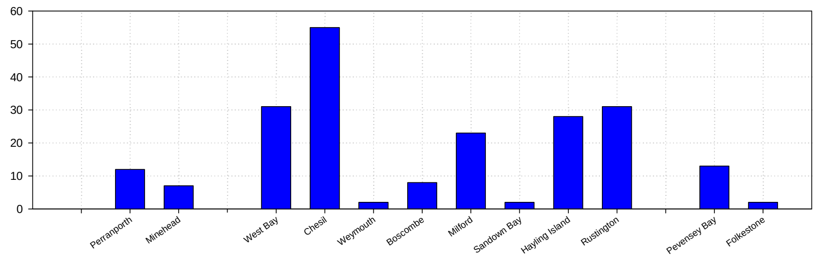


Figure 6. Number of bi-modal events in the English Channel during January 2007.

Typically, storms are defined in terms of H_s, using the Peaks-over-Threshold method (Simm ed., 1996). Over 40% of the storms experienced at Hayling Island were found to contain bi-modal seas (Figure 7).

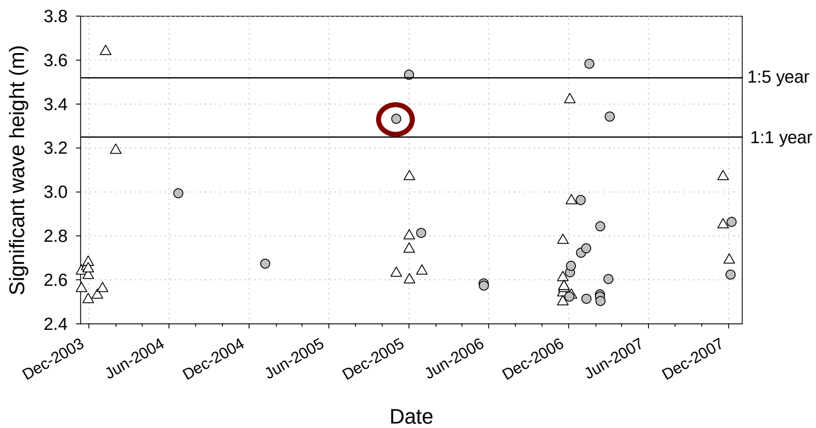


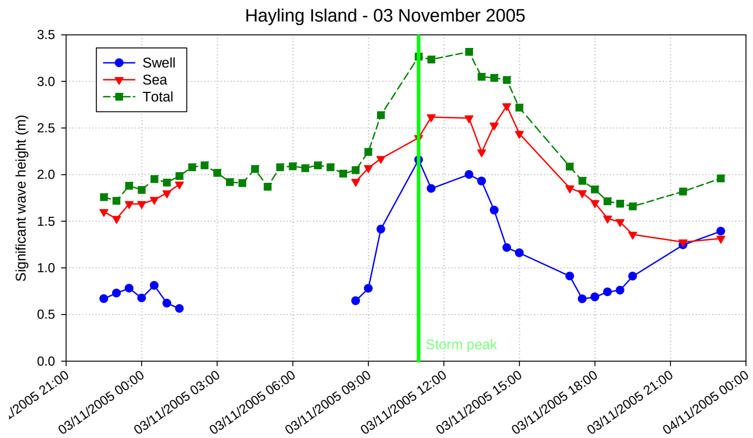
Figure 7. "Storm calendar" for Hayling Island. The peak significant wave height of each storm is shown. Filled grey circles are storms which are bi-modal events. The circled storm is 3 November 2005, as discussed below.

The 3 November 2005 storm

The storm of 3 November 2005 was particularly significant for operational coastal management since coastal overtopping and flooding were not predicted by the usual methods (typically from a combination of predicted storm surge and high waves). The storm itself was only just in excess of the 1:1 year storm at Hayling Island, whilst more extreme storms had not generated significant beach damage. The tidal range was 4.5m, with a 0.5m surge at the storm peak, but elevated tidal levels were not necessarily the main factor for flooding in this case since the position of wave breaking can be observed near the toe of the beach in Figure 8.

Figures 9 to 11 show the wave parameters and energy components for a 16 hour period centred on the storm peak, derived separately for the sea and swell components. Over 40% of the total energy was in the swell fraction, with swell wave height exceeding 2m. Furthermore, relatively low swell waves preceded the storm, but some 3 hours before the storm peak, a very long-period swell train (>14s) persisted for several hours. Such long period waves are uncommon in the eastern English Channel, but have the potential to deform beaches considerably since wave run-up is dependent on wave period.

Figure 8. Coastal flooding at Hayling Island, 3 November 2005



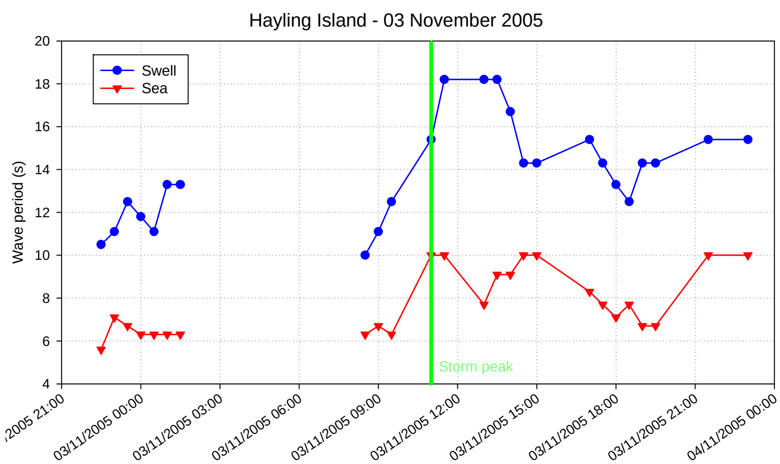


Figure 9. 16 hour time series of measured significant wave height in sea and swell components off Hayling Island, 3 November 2005.

Figure 10. Peak period of sea and swell components during 3 November 2005 storm at Hayling Island

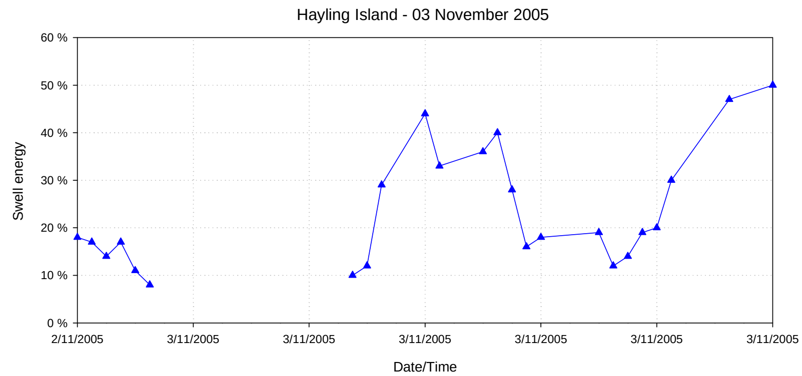


Figure 11. Swell energy as a percentage of the total wave energy.

DISCUSSION

At the majority of beaches in southern England, the operational flood warning system, run by the Environment Agency, is based on predictions by the Storm Tide Forecasting Service, supplemented by some local interpretation, including consideration of measured wave heights at the nearest monitoring station. In most cases, this is sufficient for Flood Warnings to be issued and for operational decisions to be taken. Nevertheless, it is becoming increasingly appreciated that coastal flooding can occur even though the trigger levels for coastal flooding are not reached.

A similar case to that at Hayling Island occurred at Seaton, Devon, on 24 October 2006, when coastal flood gates were not closed since trigger levels of tidal surge and wave height were not reached, yet long period waves were observed surging up the beach and the coastal road was flooded.

Events such as these lend weight to Coates *et al.*'s (1998) suggestion that more than 20% swell energy in the total wave spectrum is of consequence for beach behaviour. Furthermore, the definition of storm conditions defined purely by wave height is inadequate for prediction of potential beach damage. Thresholds of combined wave height and period are needed both operationally and for design.

For threshold conditions, however, peak wave period, T_p, has the disadvantage of being subject to rapid changes since, by definition, it represents the wave period at the energy spectrum peak. If there are two or more distinct frequency components, but of broadly similar peak energy, the time series of T_p can appear to fluctuate markedly perhaps disguising the true characteristics of a bi-modal sea. In an attempt to represent more of the lower frequency energy in the spectrum, whilst avoiding marked jumps in the time series, an additional "mean" wave period can be defined:

$$T_{m-1,0} = m_{-1} / m_0 \tag{1}$$

where the frequency moment, m_i, of the spectrum is defined as:

$$m_i = \int f^i E(f) df \tag{2}$$

and where $E(f)$ is the frequency spectrum (m^2Hz^{-1}), f is the frequency and d is the frequency bandwidth (Hz). When applied to measured data, the $T_{m-1,0}$ parameter does provide a smoother time series; this is a valuable feature for long-term modelling, and it has been used extensively in some applications of the SWAN spectral wave model (van Vledder, pers. comm.). In addition, $T_{m-1,0}$ represents a longer period than T_z (Figure 11) and has been found to be the optimal parameter to describe wave overtopping and run-up for bi-modal spectra (Van Gent, 2000, Mendez Lorenzo, 2000). Further development will be necessary to determine whether it is as adequate an indicator of the long period swell waves as T_p, for operational beach management.

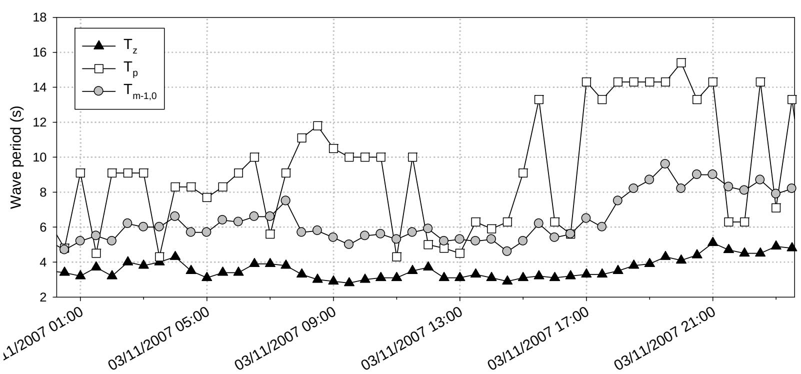


Figure 11. Time series of wave period parameters, including Eq. (1), at Hayling Island.

CONCLUSIONS

Bi-modal sea conditions can occur along the English and Bristol Channel coastline for up to 25% of the time during winter months, when up to 40% of the wave energy is low frequency swell. Such conditions can produce unexpected cut-back of beach crests and overtopping.

Future design of coastal structures, schemes and defences on the English Channel coast should consider the significance of incorporating swell energy. Significant wave height alone is a poor indicator of either wave run-up or flooding and is insufficient to provide warning of coastal flooding. Peak wave period is a useful indicator and should be integrated into operational flood warning.

ACKNOWLEDGMENTS

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