IMPLICATIONS OF THE SPECTRAL SHAPE OF WAVE CONDITIONS FOR ENGINEERING DESIGN AND COASTAL HAZARD ASSESSMENT - EVIDENCE FROM THE ENGLISH CHANNEL

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1. INTRODUCTION

Probabilistic coastal hazard assessments and design methodologies for coastal engineering structures, and in particular beaches, are based typically upon extreme storm event wave conditions of defined return period. Such conditions are usually estimated by extrapolation of long time-series of integrated parameter output produced from hindcast models or wave measurements (e.g. H_s, T_z, θ). A coupled programme of nearshore wave measurement, wave hindcasting, and measurements of beach response to extreme storm events in the English Channel, has identified some beach responses that are not characterized well by the integrated parameters. Closer examination of the measured wave data in these events has suggested that the unexpected beach responses may be related to the spectral characteristics of the storm events. Wave conditions characterized by a bi-modal distribution of wave period appear to produce more damaging conditions than is suggested by empirical models, which are based only on integrated parameters.

The basis of design or coastal hazard risk assessment is frequently derived from parametric empirical models, which use simple integrated parameter descriptors of wave conditions as input conditions. For instance, well-established empirical methods for the design of rock armour stability (van der Meer, 1988), beach recharge on gravel beaches (Powell, 1990) and predicting breaching thresholds of gravel barrier beaches (Bradbury, 2000) all rely upon such methods. Wave period is characterized usually by T_z (T_m) in these models. In each case the design methods have been developed with the aid of physical model techniques using wave conditions with a defined spectral shape (JONSWAP) where T_p=1.2T_z is considered to be a constant relationship. In some instances the impacts of spectral shape have been examined, but these observations have been confined to the examination of single peaked spectra (van der Meer, 1988) and have not identified significant response variability. The simplifying assumptions relating to spectral shape rarely replicate the prototype situation however.

Observations at wave buoys in the English Channel have identified that T_p>2T_z is not uncommon (Bradbury and Mason, 2006). Under these circumstances peak period (T_p) may be a generally more useful descriptor of period, since this identifies the period at which the energy is greatest. The situation is further complicated in situations where the wave climate is defined by a wave energy spectrum with a bi-modal period, combining swell and wind waves in varying proportions

(Figure 1). A simple definition of T_p, defined at the spectral energy peak of one of the modes may be a misleading indication of sea state under these circumstances. Analysis of spectral records from the buoys off the south coast of England indicates that the wave climate is frequently bi-modal, with clearly defined swell and wind wave components. In some instances the spectral characteristics are further complicated by bi-directional conditions, especially in the eastern English Channel (Figure 2).

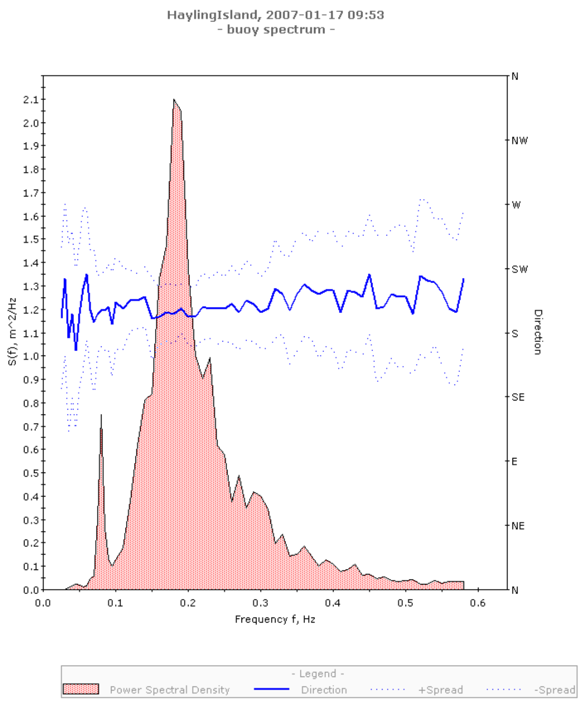


Figure 1 Bi-modal spectrum – Hayling Island wave buoy

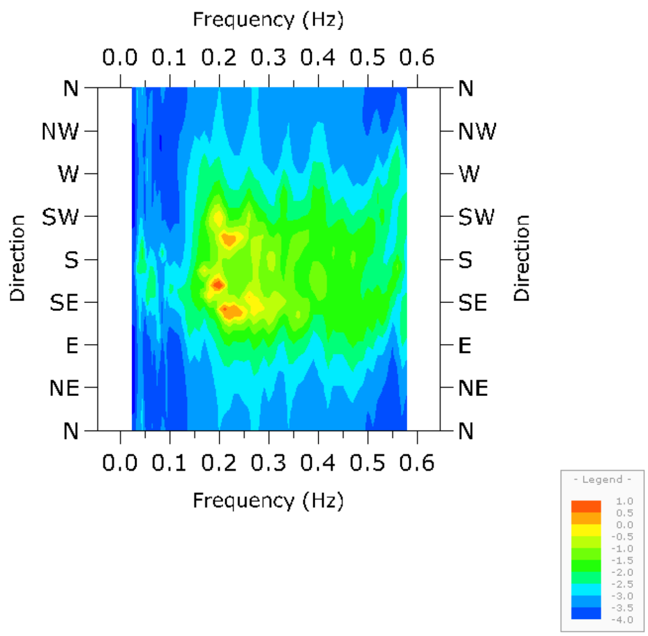


Figure 2. Bi-directional spectrum Folkestone

Possible limitations of approaches within design models that use simple integrated parameters to represent wave conditions have been identified (Coates and Hawkes, 1998). Earlier limited field observations of a single storm event on the south coast of the UK (Coates and Bona, 1997) have highlighted the occurrence of bi-modal conditions and suggested that such conditions may have a possible impact on beach profile response, which results in increased wave run-up. The swell energy component (with a H_s of about 1.15m) accounted for about 20% of the total energy in this event. Similar observations of bi-modal wave conditions were made by Bradbury (1998), when wave conditions characterized by bi-modal wave periods resulted in an unexpected beach response on a gravel barrier beach; this event was characterized by H_s =4.1m, measured in a water depth of 10m, and with spectral peak periods of 13s and 10s. Energy was divided fairly equally between the two spectral modes. Bradbury *et al* (2006) also identify similar responses arising from a series of storm events in southern England.

A small physical model investigation (Coates and Hawkes, 1998) has examined the response of a gravel beach and coastal structures to varying combinations of swell and wind waves, including bi-modal conditions. The study has concluded that a small swell, component in combination with storm waves, may result in increased wave run-up and also cut-back of the beach crest. A swell energy component of just 20% of the total energy appears to have a pronounced impact on both wave run-up and also on crest cut back. It is suggested that the impact on beach crest cut-back peaks when the swell component is about 50% of the total energy. The impacts of a smaller swell component (<20%), within a defined wave condition, has not been investigated however.

The relative distribution of wind and swell wave components around the UK have been examined over a five year period (Hawkes et al, 1997). This investigation highlights the benefits of using measured wave data as an ideal source, but is based upon routine output from the UK Met Office operational suite of wave hindcasting models, using the 25km grid model to provide systematic source data. The south coast of the UK has been highlighted as a location where significant swell components are present within the regional wave climate.

The frequency of occurrence and the relative magnitude of the various combinations of swell and wind wave combinations have not been examined in field measurements previously. Neither have the impacts of such variable conditions on structure response been examined at full scale. The random nature of wave climate makes planning of an extensive field work programme to investigate such impacts difficult.

2. METHODOLOGY

The approach adopted within this investigation focuses on application of field data from the Strategic Regional Coastal Monitoring Programmes of southern England (Bradbury *et al*, 2002); these programmes provide long-term operational large-scale regional coastal monitoring measurements of both shoreline responses and forcing conditions.

A strategic network of directional wave rider buoys has been established off the coast of southern England (Figure 3). The moored wave buoy sites are all located in shallow water (typically 10-15mCD). The buoy network has been established on a strategic regional basis, but with some focus on locations where high expenditure is needed to provide beach management schemes, for protection against coastal flooding or erosion. Sites are ideally located therefore to examine the interaction of beaches and structures with wave action. The near shore locations of the sites results in some significant dissipation of wave conditions from certain directions, as a result of the varying orientation of the shoreline and the impacts of headlands.

The principle aims of the hydrodynamic network are to generate characteristic wave climates for future coastal defence design considerations; to validate wave transformation models, particularly in areas of irregular bathymetry and; to produce data for performance evaluation of coastal engineering and beach management projects. Regional wave climates are compiled routinely, to inform large-scale strategic decision-making across 2000km of coastline (Mason, 2006). Summary integrated key parameter data (H_s, T_z, θ) are available for operational management via the project website (www.channelcoast.org), in near real time. Quality controlled archive data are also available subsequently.

Data from this network supplements synthetic hydrodynamic data derived from the UK Met Office suite of operational hindcasting models, which is generally used in engineering design. The UK waters (12km) and European waters (25km) models are 2nd generation models, which provide integrated parameter output that divides the wave climate into swell and wind climates.

Provision is made within the monitoring programme for regular post storm profile response measurements of beaches, which can be coupled with the continuous measurement of wave spectra at the buoy sites and tidal elevations from a tide gauge; these measurements have been conducted over a period of about 5 years. This long term approach provides the optimum approach to examination of irregularly occurring events within field investigations, providing data over both long temporal scales and also spread over a broad spatial scale.

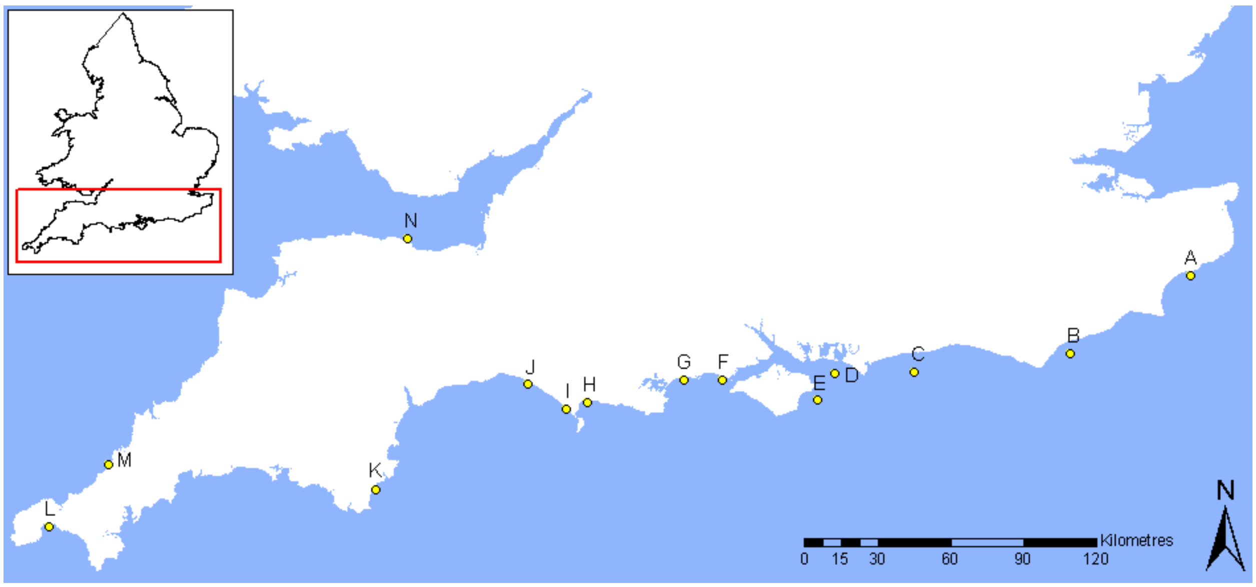


Figure 3. Location of nearshore wave measurement sites in Southern England

Key	Site	Water depth	Distance offshore (km)	First deployed
A	Folkestone	12.7 CD	1.5	2003
B	Pevensey Bay	9.8 CD	5	2003
C	Rustington	9.9 CD	8	2003
D	Hayling Island	10.2 CD	7.5	2003
E	Sandown Bay	10.7 CD	1.5	2003
F	Milford-on-Sea	10.0 CD	1.6	1996
G	Boscombe	10.4 CD	1	2003
H	Weymouth	10.6 CD	1.6	2007
I	Chesil	16.0 CD	0.4	2006
J	West Bay	11.0 CD	1.2	2006
K	Start Bay	10.2 CD	1.2	2007
L	Penzance	12.5 CD	1.6	2007
M	Perranporth	15.8 CD	1.2	2006
N	Minehead	13.0 CD	1.5	2006

2.1. Definition of bi-modal wave conditions

The configuration of various wave hindcasting models provides a range of varying methods of definition of swell conditions. The separation frequency used to divide a wave spectrum into wind and swell modes is typically based upon some combination of criteria relating to recent wind speeds or visual inspection of the spectrum; it does not occur at a constant frequency. Each model varies slightly in its definition of the separation frequency. Some approaches allocate more energy to the wind sea than others. For example, some methods include factors such as reductions in wind speed or changes in direction, which may result in apparent swell; this approach may result in a higher swell allocation to the climate than other methods (Hawkes et al, 1997). Wave energy below the separation frequency is assumed to be swell, whilst higher frequency energy represents wind waves. There is no generally accepted precise definition of wind and swell sea however.

Models and theoretical descriptions of bi-modal events typically provide an oversimplification of the spectral shape, and are usually characterised by spectra with two clean spectral peaks, with well-defined separation frequencies. Significant variability of spectral characteristics has been observed, when comparing hindcast models with nearshore wave measurements. Comparisons between modeled and measured spectra suggest that the latter are generally less clean and well defined than those produced from numerical modeling, hence the separation of the wind and swell components is less easily defined. The problem is compounded when examining individual events. The limited frequency resolution of the Met Office UK Waters model contributes to this simplification process and has previously been shown to produce a wide scatter of results when model wave period measurements are compared against measured wave conditions (Bradbury et al, 2004).

The swell component is defined on the basis of the work by Golding (1983) within the Met Office model. The separation frequency of wind and swell is defined on the criteria:

$$F > 0.8 f_p \qquad \text{(e1)}$$

$$|\alpha| < 90^{\circ} \qquad \text{(e2)}$$

where f_p is the spectral peak frequency and α is the difference between the wave direction and the wind direction. An iterative procedure is used to determine the unknown peak frequency. The total wind sea energy (E_w) is calculated and a new f_p determined from the approximation:

$$f_p = (2.5\times10^{-4}/E_w)^{0.25}$$

The total energy in the wind wave component is recalculated and a JONSWAP spectrum computed from $E_{w.}$ using an approximation of the single parameter model of Hasselmannn et al (1976). The full JONSWAP spectrum is used to represent the wind wave spectrum. The swell component is subsequently extracted on the basis of the defined peak frequency and criteria in (e1) and (e2).

Since the purpose of this investigation is to address the potential influence of bi-modal (wave period) conditions on beach and structure response, the qualifying criteria have been modified so that only those events with a significant energy level are considered within the analysis. The approach for definition of appropriate bi-modal conditions for analysis of the measured wave spectra derived from the wave buoy network has been refined within the current investigation and is outlined below.

In the first instance a procedure is identified that is used to subdivide the spectrum into swell and wind wave components. In order for a spectral condition to qualify as a bi-modal spectrum within this investigation the following criteria must be met for each 30-minute spectral record. The minimum total energy within the spectrum must provide an overall H_s>=0.5m. The smaller of the two spectral peaks must be at least >0.33 of the larger peak and must also have a power spectral density of >0.4m^2/H_z. The energy of the trough must also be <= half the energy of the smaller peak. These criteria are essentially to ensure that there are two distinct peaks in the energy in each of the spectral bands and that there is a reasonable amount of energy within each band. A separation frequency has subsequently been defined for each individual spectrum; this typically occurs at a frequency of about 0.09-0.1H_z. This approach provides the first filter to exclude many conditions.

Although the design and analysis of performance of most coastal engineering structures is defined by wave climate statistics that are based upon 3-hourly records, durations of 30-60 minutes can be significant in terms of either beach or structure response. For instance, a gravel beach is considered to approach its equilibrium profile shape after just 500 waves (approximately 1 hour for 7 second waves) (Powell, 1990). Similarly, overtopping or the onset of breaching of a barrier beach structure may be significant over such durations. The established approach to definition of wave climate, based on 3-hourly records, is historical and is based on the physical computational and storage limitations of old technology. Extreme events of significantly worse proportions may be expected over shorter durations and these are most certainly significant in terms of structure performance (Bradbury et al 2004). On this basis, events with duration of one hour were considered to be of significant persistence and these are used within subsequent analysis for this investigation. The second filter criteria used to define a bi-modal event requires an event with a minimum persistence of one hour. Subsequent filtering of the time series of spectral records identifies those events with at least two consecutive 30minute records that meet the qualifying criteria.

Since the primary objective of this investigation is to examine whether bi-modal conditions should be considered further as a design condition for coastal engineering and coastal hazard assessment, an overview of the frequency of occurrence of bi-modal conditions is required.

Definition criteria outlined above have been used to filter data from a two year time series of spectral records derived from each of the buoy sites within the southeast and for 1 year from the less mature sites from the southwest. Data are expressed as a percentage of the total time series record, for each of the buoy locations.

3. RESULTS

3.1 Spatial variability of bi-modal conditions

Summary records are shown for the analysis period at 14 near-shore wave buoy locations in the English Channel. The total annual percentage of bi-modal events is shown for each site. Noticeable spatial variability of the bi-modal conditions occurs throughout the English Channel (Figure 4).

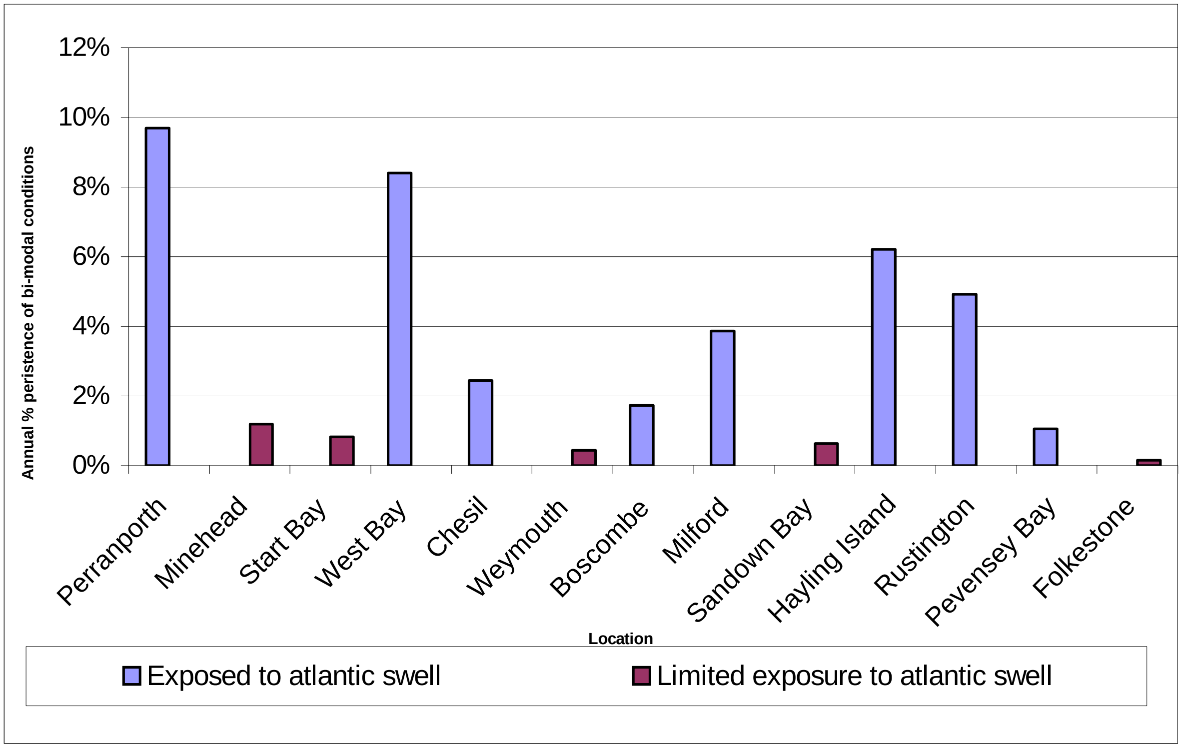


Figure 4. Spatial variability of bi-modal conditions over a two-year period

Swell conditions that arrive at the south coast of the UK are generally generated from the southwest, as a product of Atlantic depressions. As the wave buoy sites are all at near-shore locations, several sites within the network are protected from the long period wave activity by headlands that dissipate or dampen such southwesterly swell conditions (Figure 3); these include Start Bay, Weymouth, Sandown Bay and Pevensey. The proportion of swell and bi-modal conditions observed at these sites is noticeably lower than at other locations. It is argued that it is not necessary to consider the influence of bi-modal conditions within coastal hazard assessments at these locations on this basis, and that the integrated parameters alone are adequate to describe the wave climate for the purposes of coastal engineering design at these sites.

Similarly, conditions on the northern coast of the southwest penninsula are also less prone to swell conditions due to dampening from land masses (Minehead) although the site at Perranporth remains open to the Atlantic swell and is subject to regular swell conditions. There is a noticeable reduction in swell conditions at the eastern end of the English Channel (Folkestone) and for this reason bi-modal criteria are virtually never met. Dampening of swell conditions occurs here as a result of the protective influence of the Brittany coast of France.

Sites that demonstrate a significant proportion of bi-modal conditions include Milford-on-Sea, Hayling Island, Rustington, Boscombe, Chesil Beach, West Bay, and Penzance. The Hayling Island site presents a particularly interesting case, since an initial examination of this site suggests that some sheltering from swell waves may be provided by the Isle of Wight. The observations of swell conditions appear to be more pronounced than at other sites however; it is suggested that the local bathymetry results in wave transformations that help to focus swell conditions at this site. Partial sheltering is offered also to the Boscombe site, which limits the frequency of swell events at this site. The data set for the Chesil buoy site may not be representative of a full year as the record only covers a period of 10 months and omits two winter months.

These observations provide a localized refinement of the results of the investigation based upon hindcast data from the Met office European Waters model (Hawkes et al, 1997). Conditions used in Hawkes investigation were based upon model grid points that are away from the influence of either shallow water transformations, or the influence of coastline features and orientation.

3.2 Annual temporal distribution of bi-modal conditions

Monthly summary records of bi-modal conditions are shown for all sites for two years duration (where possible). The graphs of monthly distribution of conditions (Figure 5) demonstrate that bi-modal conditions are much more frequent during the winter months, but that there is also some significant level of inter-annual variability. For example, the winter of 2006/07 has included a significantly higher proportion of bi-modal events than 2005/06.

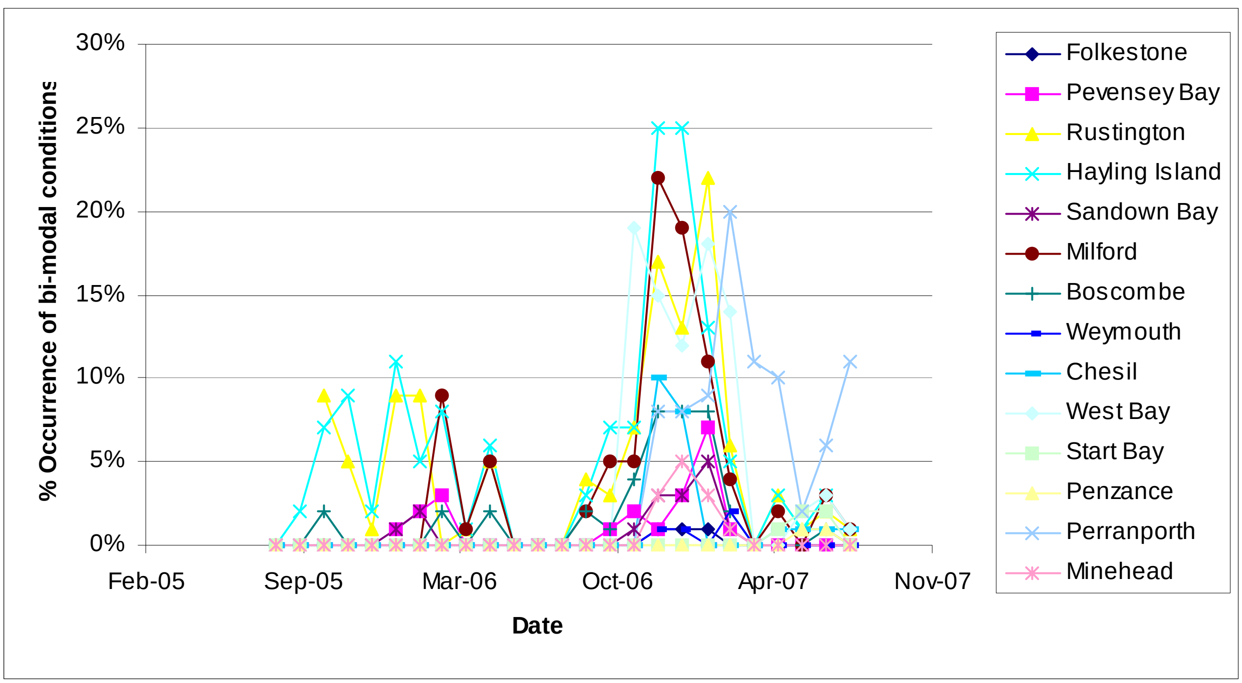


Figure 5. Monthly persistence of bi-modal wave conditions over a 24 month period measured at nearshore wave buoy sites in southern England

The frequency of occurrence of bi-modal conditions within the western and central English Channel during winter months presents an alarming picture, considering that coastal engineering design and coastal hazard risk assessment criteria do not generally take account of these conditions. Measured wave spectra suggest that bi-modal conditions (as defined above) have persisted for as much as 25% of the time during some individual months.

Further examination of records at the Hayling Island site over an extended period of time suggest that the observed temporal pattern is typical (Figure 6), although the intensity of the swell component varies significantly from year to year.

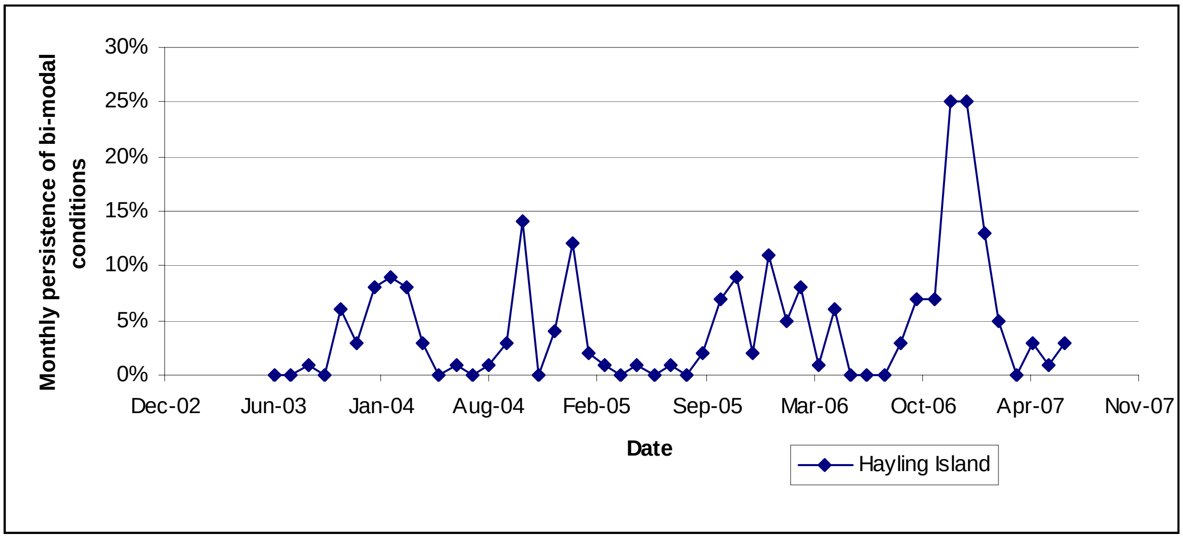


Figure 6 Interannual variability of time series distribution of bi-modal conditions at Hayling Island Buoy site.

3.3 Temporal distribution of storm events

A storm calendar is produced routinely for each wave buoy site within the monitoring programmes, using a peaks over threshold method to define each storm event (Simm ed, 1996). Each storm is then examined in detail, for the period 16 hours either side of the storm peak, so as to include both the build-up and decay of a storm typical of a mid-latitudes depression. The threshold considered for the storm calendar at each site is derived empirically and is based typically on the 0.05-0.1% exceedance level; this is typically determined from a measurement time series of 5 years duration. The return period frequency of these events is determined using the traditional method of extrapolation of time series of integrated parameters, based on a three parameter Weibull distribution, and using events with 3-hours duration as the basis. An example is presented for one of the buoy sites, which appears to be subject to regular bi-modal conditions (Figure 7).

The threshold used for development of the storm calendar is H_s =2.4m for Hayling Island. Note that the events over threshold duration criteria used to define a storm event differ from those used in the statistical analysis of return periods, which are based purely on persistence of events of three hours duration. This method of presentation provides an at-a-glance indication of the relative storminess and distribution of storms characterized by both single peaked and bi-modal spectra during the course of a number of years.

A time series of individual storm events is considered. Both storms that are defined by bi-modal and single spectral peaks are shown, and which also meet the events over threshold criteria as described above. Events that might be considered to be bi-modal are highlighted; these demonstrate that a significant proportion of the storm events are characterized by bi-modal conditions.

The 1:1 year return period (3 hour) storm event is shown at a significant wave height of 3.3m and the 1:5 year event at 3.5m. In design terms these conditions would typically be associated with a wave period (T_p) of 7.7-8.2s., based on the assumption of a constant wave steepness for the extreme events. For the purposes of this investigation the peaks over threshold storm event has been set to Hs=2.4m which has a return period of about 20:1 years, thereby including a number of smaller events that would not normally be considered to be of significant magnitude to cause any damage to either beaches or structures. A total of 41% of the 27 events above threshold are considered to be bi-modal using the criteria defined for this investigation. This is significant since the methods used for coastal hazard risk assessment and engineering design are based typically upon extremes derived from integrated parameters, and assuming a simple JONSWAP shaped wave energy spectrum. Two of the three most severe storm events were characterized by bi-modal conditions at this site, within a two-year period.

The observed pattern is similar at other sites within the network which also include a similarly high proportion of storm conditions with bi-modal characteristics. On this basis further investigation of the structure of the events and the response of beaches and structures appears to be worthwhile, for these sites.

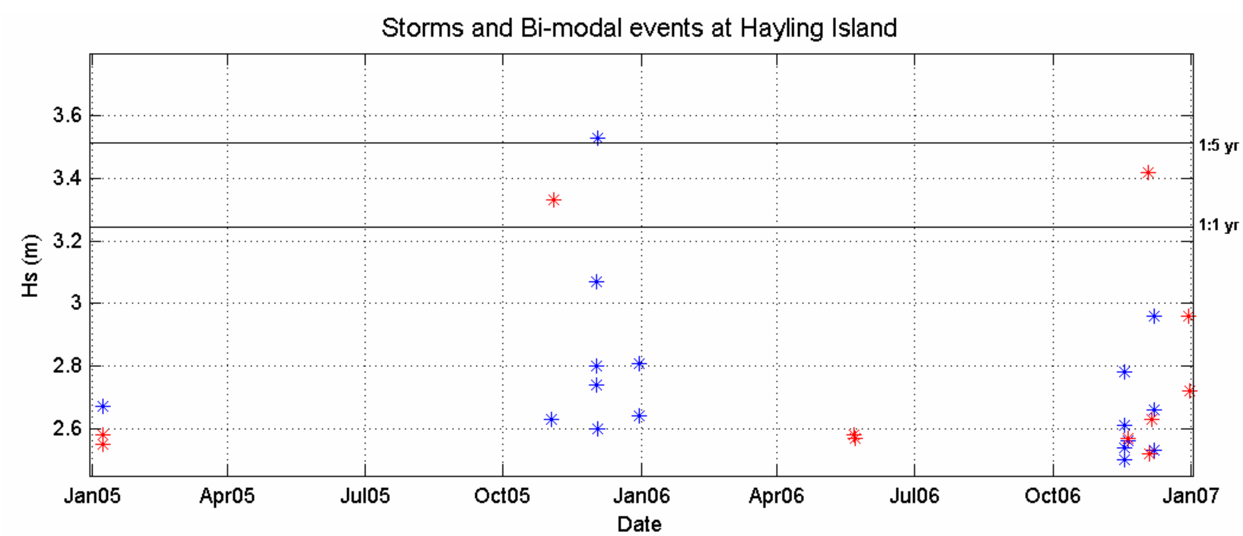
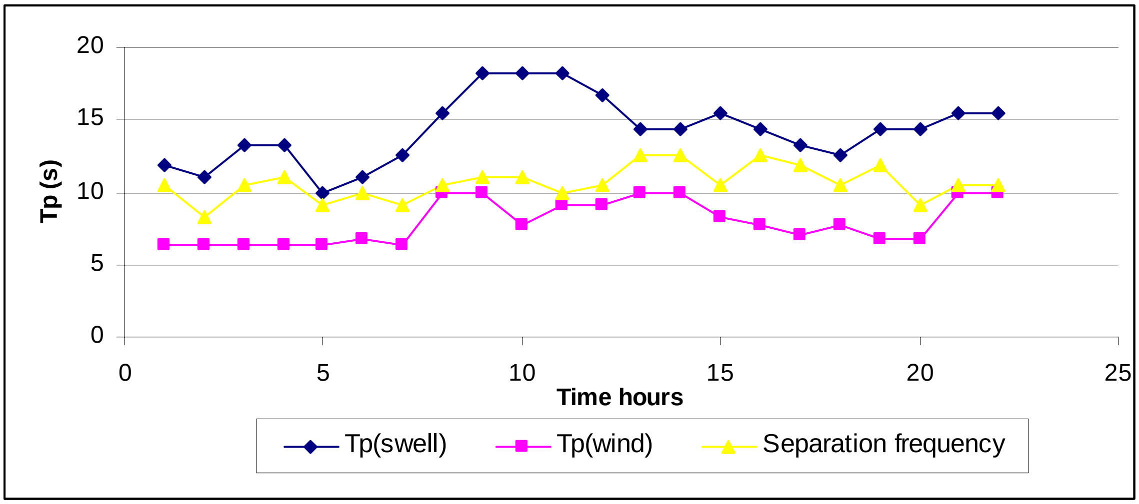


Figure 7 Storm calendar for Hayling Island showing distribution of storms with bi-modal and single mode spectra

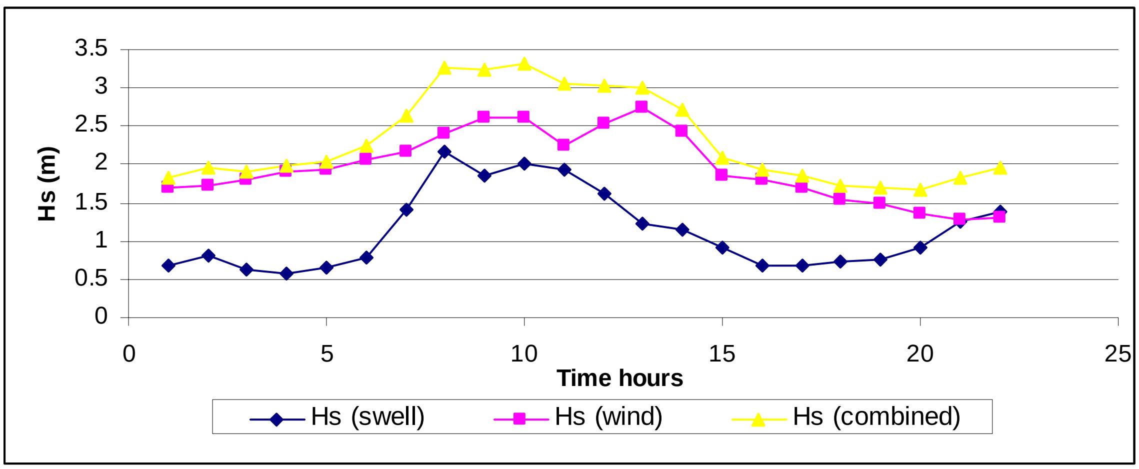
3.4 Characteristics of individual storm events

Examination of the spectral characteristics of some of the most severe events within the storm calendar record enables the temporal profile of each storm event to be considered. The characteristics of those events, which have exceeded the 1:1 year return period threshold, are examined in detail. Examples are presented for two events measured at the Hayling Island buoy (Figures 8 and 9).

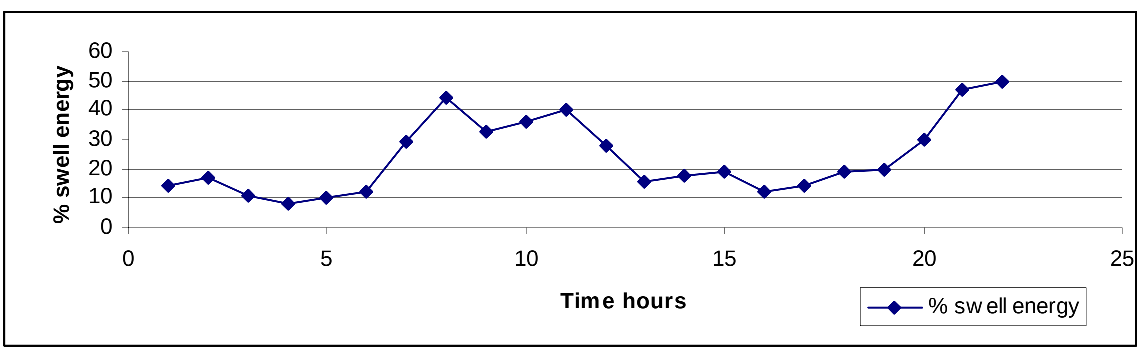
Firstly, the storm event of 3 November 2005 is considered. The peak of this event has a return period of about 1:2 years, defined on the basis of traditional extrapolation of the integrated parameters, using H_s. The whole of the storm event is characterised by bi-modal conditions, with a swell component evident throughout. The separation frequency remained fairly constant at about 0.1 Hz and wind waves are characterised by T_p of 10s (Figure 8a) and H_s of 2.5m (Figure 8b) over the storm peak. The swell component of the storm is energetic, with a variable peak period, reaching 18s, and with H_s=2m over the peak of the storm. The energy of swell and wind wave components peak together during the storm peak and the swell energy during the peak of the storm is typically about 40% of the total energy. These in phase characteristics enable the storm to be defined in simple terms, with an obvious coincidence of swell and wind waves.



(a) Wave period (Tp) and separation frequency



(b) Significant wave height



(c) Percentage swell

Figure 8. Temporal distribution of wave height, period and percentage swell conditions for storm event of 3 November 2005 at Hayling Island buoy site.

The buoy network provides evidence of the propagation of long period swell throughput the English Channel. Progression of the arrival of swell through the English Channel (Figure 9) within the storm of 25/1/06, is denoted by the sharp jump in $T_{p,}$ derived from the integrated parameter output. Note that the swell component is more accentuated in the western Channel, becomes less well defined from west to east and disappears entirely by Folkestone. In forecasting terms, knowledge of the timing of the arrival of swell would be advantageous and this is an area of predictive work where beneficial development could take place.

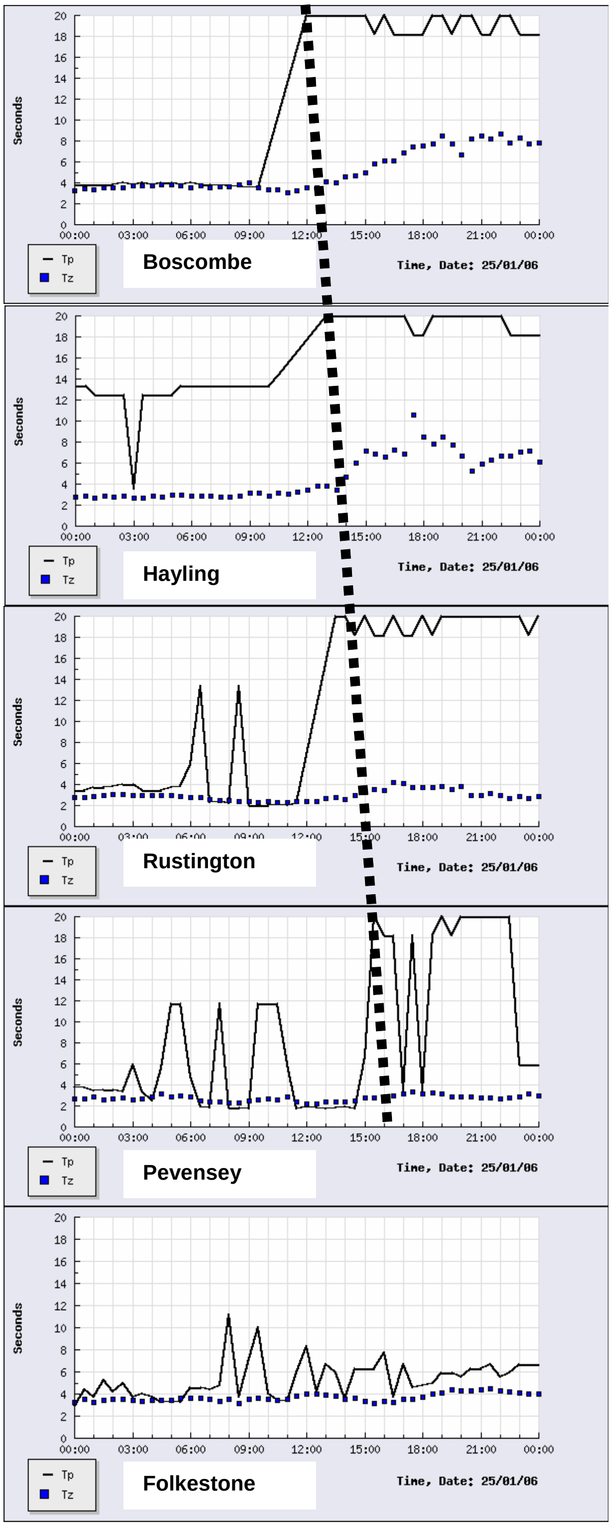
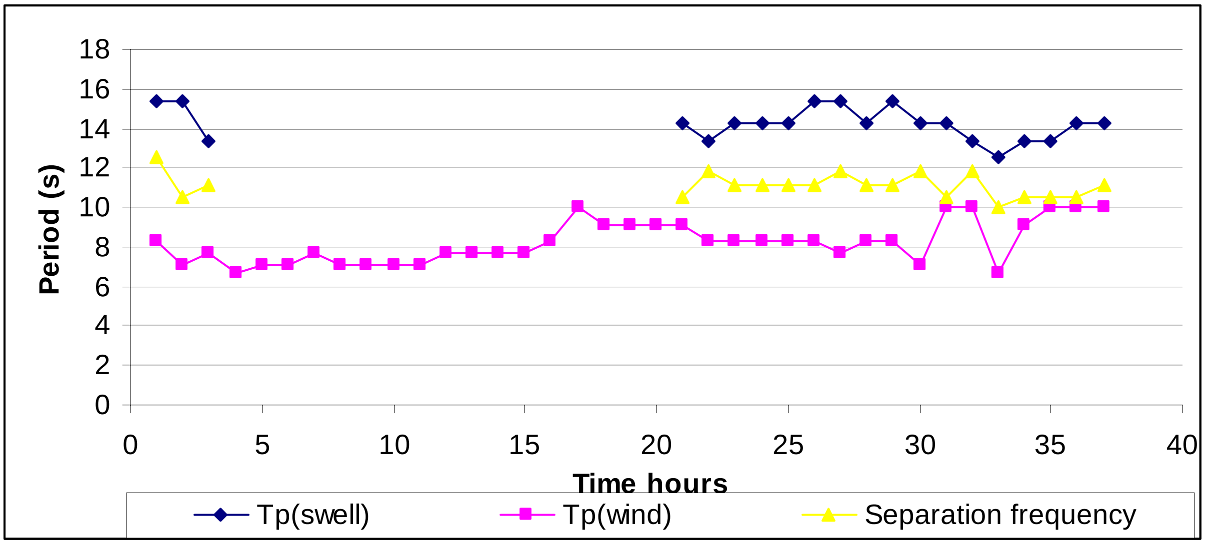


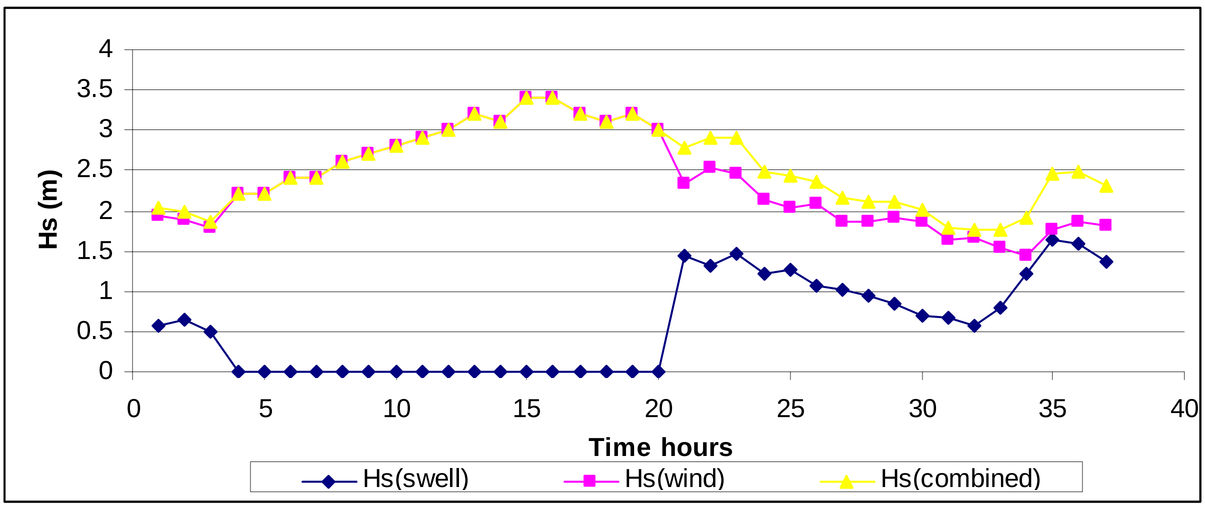
Figure 9 Arrival of swell conditions throughout the English Channel for the storm event of 25/1/06

The storm event of 3 December 2006 measured at the Hayling Island buoy site is also considered. The characteristics of the storm profile differ significantly to that of the event of 3/11/2005. The storm peak of the 3/12/2006 event (Hs=3.4m) has a return period of about 1:3 years. This peak occurred prior to the arrival of a significant swell component however, and at this stage the event could not be considered to meet bi-modal criteria (Figure 10b). The arrival of swell conditions part way through the storm result in bi-modal criteria being met, but at a lower overall Hs=2.9m.

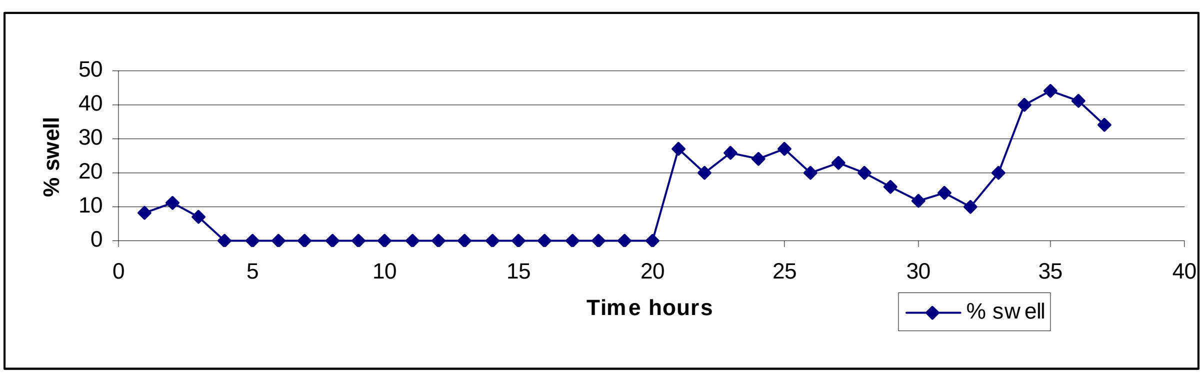
Wind waves are characterised by T_p of 8s (Figure 10a) and H_s of 3.4m (Figure 10b) over the storm peak. On arrival of swell conditions, the separation frequency is evident at about 0.09 Hz. The swell component of the storm is characterized by a variable peak period, reaching 13-14s, and with a swell H_s=1.5m over the peak of the swell wave component. Significantly, the peaks of swell and wind waves are out of phase. No significant swell energy is present over the storm peak, but the swell component provides about 25% of the total energy at its peak. The overall significant wave height is lower than at the storm peak, but is nevertheless still energetic, reaching Hs=2.9m at this stage.



(a) Wave period (Tp) and separation frequency



(b) Significant wave height



(c) Percentage swell

Figure 10. Temporal distribution of wave height, period and percentage swell conditions for storm event of 3 December 2006 at Hayling Island buoy site.

The out of phase characteristics exhibited by the event of 3/12/2006 present further difficulties when considering how best to develop a simple framework of probabilistic design definitions that are capable of parameterising bi-modal conditions, for subsequent application in coastal engineering design or coastal hazard assessment. Examination of time series of spectral records for all sites and for many individual storms confirms that such an out of phase coupling of wind- and swell-waves is much more typical than in phase coincidence of the energy peaks. Additionally, the relative proportion of swell and wave energy usually varies throughout the course of the storm. The number of variables in a joint probability definition of conditions is compounded and must include therefore variables that include the following: wind and swell wave heights and peak periods, and relative proportions of energy within each of the spectral modes. These must be identified for each time step. A time step interval of one hour is suggested as a suitable duration, for the purposes of analyzing the performance of beaches and for overtopping.

3.5 Beach performance during storm events.

The monitoring programme makes provision for regular beach surveys following storm events, which have exceeded a predefined threshold; this typically equates to an event with a return period (H_s) of at least 1:1 year. Regular surveys have been carried out of beach responses to storm events; these include events that are characterized by both bi-modal and uni-modal conditions. The spectral characteristics of storm events have been examined and comparisons of the profile response made with empirical predictive models of profile response and breaching, which are based upon the use of simple integrated parameters and single peaked spectra.

Overtopping was reported at numerous sites on the south coast and overwashing of the gravel barrier at Medmerry and Hurst Spit were both reported during the event of 3/11/2005. Flooding associated with extreme wave run-up was observed at Hayling Island. Application of the integrated parameters within empirical models did not predict such responses. Similarly, events with less frequent return periods, defined by more severe integrated parameter characteristics, have been observed on numerous occasions at these sites; these events have not resulted in such damaging conditions, when the wave energy spectrum has been defined by a single peak.

A range of storm events have been monitored at Hurst Spit, Hampshire, UK, a gravel barrier beach, and results compared with a predictive model of gravel barrier response (Bradbury, 2000). The model predictions appear to give reasonable results for many instances where the conditions can be defined by single peaked spectra. The beach response in bi-modal spectra has been somewhat worse than predictions would suggest however. Notable responses resulting in overwashing of the crest, which was not predicted by the model, have occurred during the storm event of 3/11/2005. Similarly, increased cutback of the beach crest ridge has also occurred during numerous bi-modal events, including the storm event of 28/10/1996. The requirement for relatively extreme combinations of wave and water level conditions to result in overwashing at this site has resulted in relatively few documented events of significance. Similar applications of the model have also been conducted of the gravel barrier at Medmerry which have resulted in similar responses.

As the beach performance is dependant upon many variables, considerable data is required to develop a robust empirical framework that can quantify the beach performance relative to bi-modal criteria. Events of interest are generally considered to be extreme (>1:1 year) and the rate of data collection is controlled by this restriction. The programme is currently of inadequate maturity to provide sufficient recorded events to develop a robust modification to the empirical framework, based upon bi-modal conditions. Continued long term observations are planned to extend the framework and to develop design conditions that include bi-modal criteria.

4 CONCLUSIONS

Wave conditions characterized by bi-modal wave periods within the English Channel persist for 25% of the time during some winter months, at sites that are exposed to swell conditions from the southwest.

Storm conditions in the English Channel include a significant proportion of events that are characterized by bi-modal spectra; these may exceed 40% of storm events at some locations.

Bi-modal conditions appear to have a particularly significant effect on the profile performance of beaches, impacting on run-up, crest cut-back, and overwashing of gravel barriers and on the overtopping of seawalls. Longer-term data sets are required to develop a robust empirical framework to quantify the impacts of these conditions.

Bi-modal wave conditions may need to be considered as a design variable for some areas of the English Channel coast, in addition to the usual extreme wind-wave conditions. Alterative definitions of wave climates are needed to enable a statistical description of bi-modal conditions.

New design methodologies are required to consider the impacts of bi-modal conditions on the design of coastal structures.

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