Beach Recharge Design and Bi-modal Wave Spectra

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Abstract

Recent field and laboratory research indicates the potential importance of complex wave spectra (combining swell and wind sea) in the design of gravel beach recharge schemes. The paper discusses the research and introduces a swell wave atlas as an aid to understanding the occurrence probability of complex wave conditions around England and Wales.

Introduction

Gravel beaches are found on the shores of many parts of the world, and are of particular importance along stretches of the heavily populated south coast of England where they are known as shingle beaches. Fully developed shingle beaches provide an excellent barrier against erosion or flooding. Unfortunately they are becoming depleted due to a lack of natural sediment supply and modifications to natural processes caused by coastal works (harbour construction, dredging, beach control structures). Shoreline managers are increasingly using beach recharge as a method of improving beaches for coastal defence purposes.

Design of shingle beach recharge schemes in the UK over the past ten years has relied heavily on a parametric beach profile model developed at HR Wallingford (Powell, 1988). The model was developed from an extensive mobile bed wave flume study using waves defined by JONSWAP spectra; effects on wave height and period, water level, sediment size and underlying impermeable layers are all considered.

Results from three recent research projects indicate a possible weakness in the model, and in all other beach or structure response models that are driven by simple wave conditions, whether numerical or physical. These results provide evidence of the potential importance of complex wave conditions that combine wind sea and swell, forming a wide spectral distribution that can separate into two distinct peaks or a bi-modal spectrum. These conditions arise when locally generated storm seas occur in conjunction with longer period swell waves.

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The projects discussed in this paper include:

- Field work that recognised the occurrence and potential importance of bi-modal wave conditions.
- Development of a swell wave atlas for England and Wales that identifies the coastal areas likely to be affected by bi-modal conditions.
- A wave flume study that investigated the response of beaches under laboratory conditions.

The paper also touches briefly on further flume studies that looked at the impact of bi-modal waves overtopping seawalls and the stability of armour stone revetments.

The research projects were all funded by the UK Ministry of Agriculture, Fisheries and Food under their Flood and Coast Defence programme. Detailed descriptions of the work and the full results are presented in Coates *et al* (1998), whilst discussions and conclusions are presented in Hawkes *et al* (1998).

Field study

The response of shingle beaches to long period wave conditions has been noted and observed many times, but quantitative data regarding sea conditions and beach profiles are not generally available. An exception to this is the data set collected at a recharged beach at Highcliffe in Christchurch Bay on the UK south coast (Coates & Bona, 1997).

The Christchurch Bay field site is within an embayment and is partially protected from wave attack by headlands and an offshore reef. The steeply sloping upper beach is formed of shingle (5mm-50mm), while the lower beach comprises a wide sand platform. A three year study was commissioned to record the post-construction development of the recharged beach and to determine the effectiveness of the design process. Measurements were taken of beach profiles, sediment distribution, wave conditions and water levels.

Over the first two years the beach crest remained relatively stable, with variations of +/- 0.1m from the design elevation of 3.9mOD. This apparent equilibrium situation changed during a storm in late December 1994. The post-storm survey showed a distinct rise of the crest elevation to 4.3mOD. Initial analysis of the field data showed that the storm event was not unusual in terms of pre-storm beach profile, storm sequence and duration, peak water levels or maximum significant wave height. In most respects it was apparently similar to the previous storm in early December 1994, during which the beach crest had shown no increase in elevation. As there was no obvious reason for the difference in beach response a more detailed analysis of the wave record was undertaken.

The maximum recorded significant wave height was 3.17m for the 7-8 December and 3.14 for the 29-30 December. Plots of the wave spectra for these two events (Figure 1) show that the headline wave heights were misleading. The early December storm gave a typical wind sea spectra with a single peaked energy distribution (dashed line). The post-Christmas storm shows a distinctly different distribution (solid line); the bi-modal shape comprises a less severe wind sea overlying a 15-20 second swell. The swell accounts for about 20% of the total energy and gives an estimated 1.15m wave height.

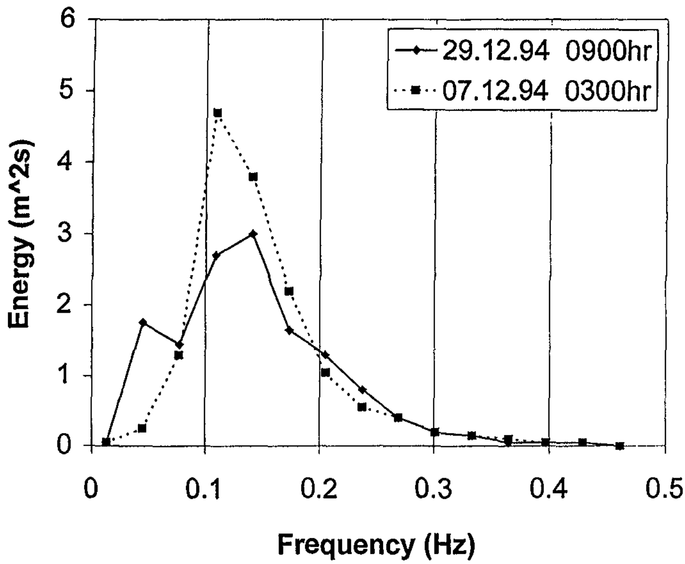

Figure 1 Storm wave spectra: 7-8 Dec and 29-30 Dec, 1994

Although these field records of beach response and wave spectra did not form conclusive evidence, they did suggest that bi-modal wave conditions could be important to beach recharge designs. Schemes designed using simple wave conditions could under estimate the equilibrium beach crest elevation and therefore the total volume of material required to provide coast protection. The field results were of sufficient interest to justify further work, first on the occurrence probability of complex wave conditions and second on a wave flume study to extend the beach response investigation under laboratory conditions.

Swell wave atlas

An atlas of offshore swell wave conditions around England and Wales has been developed (Hawkes *et al*, 1997), based on the UK Meteorological Office (UKMO) wave model for European waters. The UKMO model predicts both wind sea and swell waves at three hourly intervals for points on a 25-30k grid around Europe. Five years of data from the grid points around England and Wales were analysed to estimate extremes and were then presented as representative conditions for twenty five coastal areas. The atlas information is broken down by swell wave period and probability of occurrence. Figure 2 shows the distribution of UKMO grid points and the coastal areas. Figure 3 presents the swell wave distribution (H_s vs T_m) for the area of the field study over the five year analysis period.

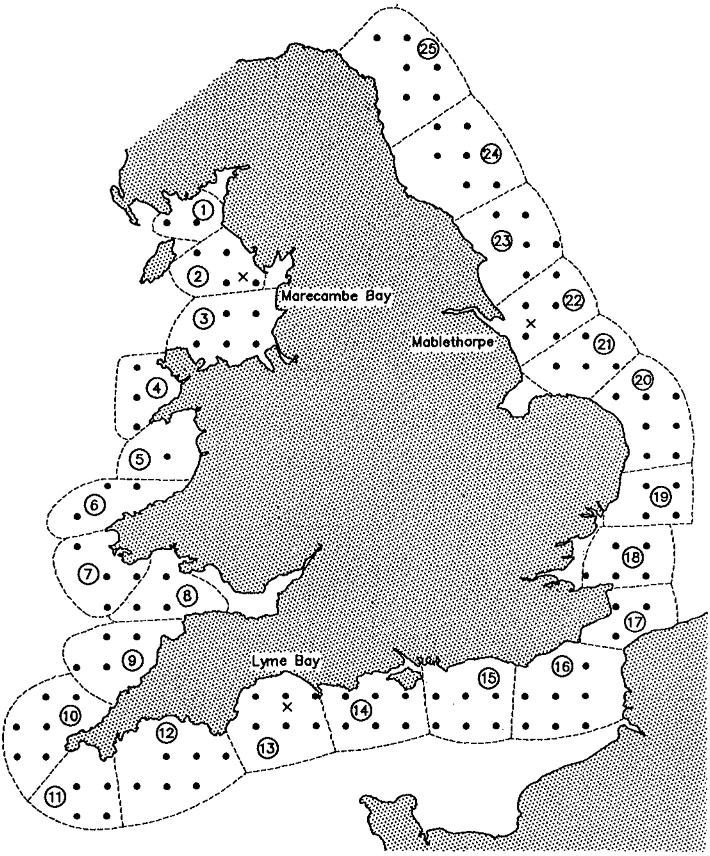

Figure 2 UKMO grid points and wave atlas areas

From the basis of this new swell wave information and an existing knowledge of wind sea climates the authors were able to consider their joint probability of occurrence. The interdependence of swell and wind sea were considered and correlation coefficients were proposed for each of the twenty five coastal areas. The results are presented as a series of tables of the range of wave combinations that have return periods from 1 to 100 years. In most locations the wave energy for a given return period is greatest for the wind sea only condition, while the swell wave only condition has the lowest energy; bi-modal conditions of combined wind sea and swell fit between these two limits. The shape of the energy curve for different wave combinations is critical in determining the potential importance of bi-modal conditions at any given site.

Figure 4 presents the energy distribution curve for Lyme Bay on a moderately exposed part of the south-west coast of England. The energy level drops away with increasing percentages of swell energy, but the rate is dependent on the swell wave period. Interestingly, for the same return period the total energy for wind sea only is approximately equal to wind sea plus a small percentage of swell; this observation is of importance in relation to the non-linear wave flume results presented below.

The shape of the energy curves is dependent on exposure to swell, exposure to storms and on local bathymetry. Further information on the development of the swell atlas is presented in Hawkes *et al* (1997).

Wave flume study

A physical model study was commissioned to investigate shingle beach response to varying combinations of swell and wind sea under laboratory conditions. The model was built in a 45m flume with a working water depth of 800mm. The required ranges of simple and bi-modal spectra were generated by an electro-hydraulic piston paddle to a notional scale of 1:20. Equipment included camera, video, automatic profiler and wave probes. The mobile beach simulated a typical UK shingle beach. It was formed of crushed and graded anthracite coal scaled according to well established and field validated principles that reproduce threshold of motion, fall velocity and beach permeability (Powell, 1988).

The test programme looked at beach response under six sequences of wave conditions. The five tests comprising each sequence had a constant total wave energy but varying proportions of swell and wind sea. The tests did not consider the probabilities of occurrence that can be derived from the swell atlas for specific sites.

Initial tests in each sequence used wind sea only. These were followed by three bi-modal spectra tests with an increasing percentage of swell energy relative to total energy. The final test used swell only. Figure 5 presents the spectra for one of the test sequences. Energy levels and peak swell periods for all of the sequences are presented in Table 1.

Table 1

Sequence	Equivalent wave height (H_s)	Swell period (T_p)
1	2.12m	11s
2	2.12m	19s
3	2.83m	11s
4	2.83m	14s
5	2.83m	19s
6	3.53	11s

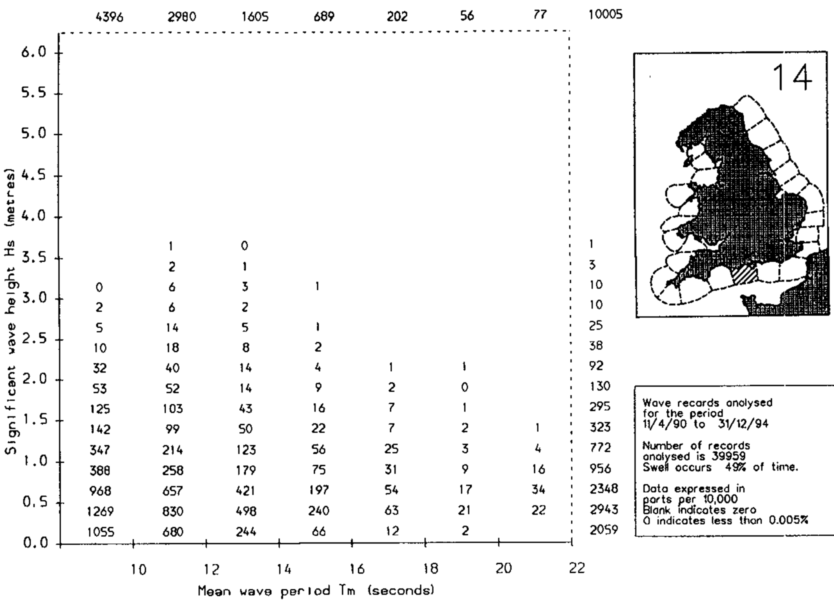

Figure 3 Sample swell wave distribution plot (central south coast of England)

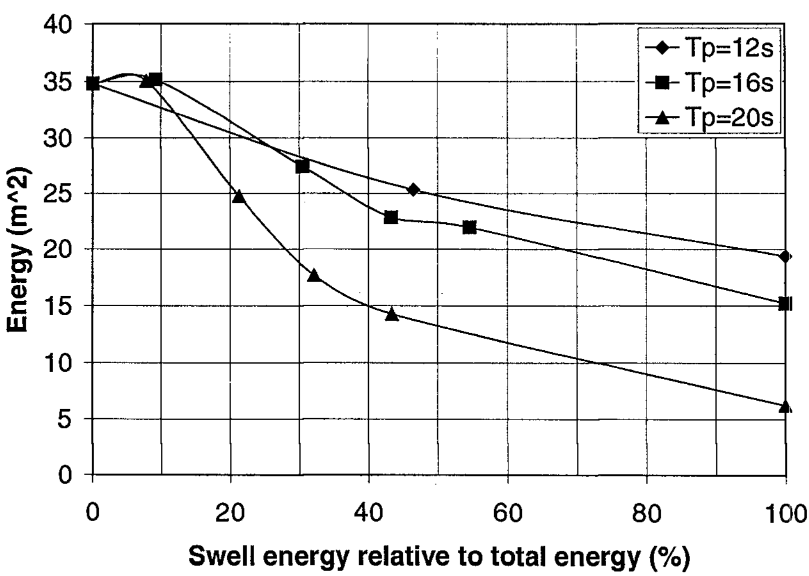

Figure 4 Wave energy curve for a range of swell/wind sea combinations with an equal return period (Lyme Bay)

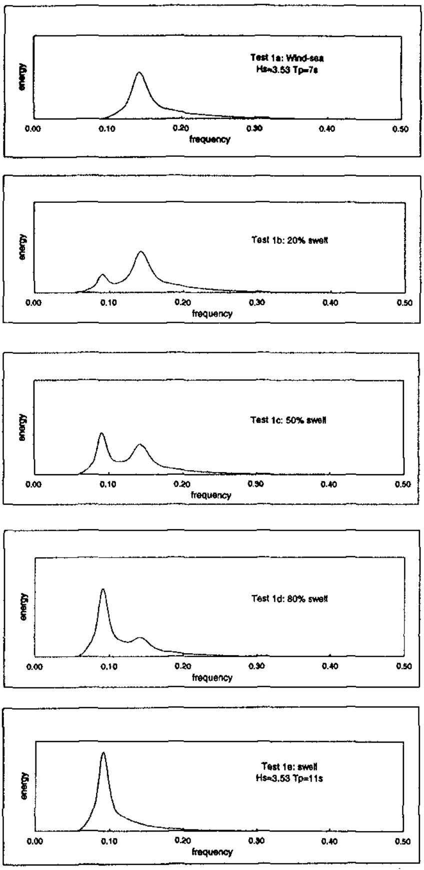

Figure 5 Typical wave energy spectra for test sequences

Complete cross-shore beach profiles were measured after each test using the automatic profiler. Analysis concentrated on the elevation and cross-shore location of the crest relative to the initial beach water line. These two parameters are considered critical indicators of shingle beach response under storm conditions and are important to beach nourishment design.

Figure 6 shows the variation in crest elevation with increasing percentages of swell at periods ranging from 11s to 19s. The wind sea only condition has an H_s of 2.83m and is taken as the reference against which the other conditions are compared. The crest elevations have been non-dimensionalised to a percentage increase relative to the wind sea only result.

The elevation response to increasing amounts of swell energy and swell period are non-linear. The rate of elevation change decreases when swell accounts for more than 50% of total energy and when swell period increases above 14s.

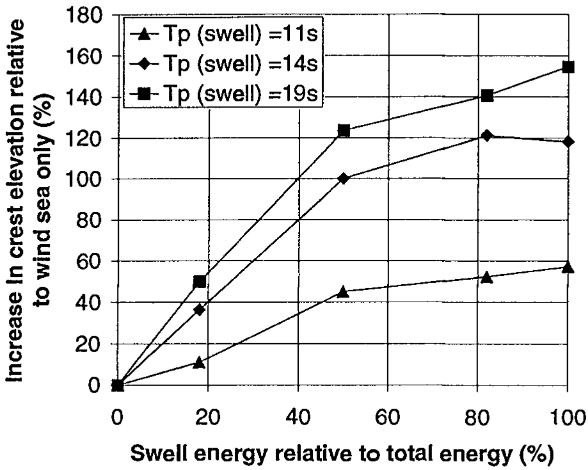

Figure 6 Relative shingle beach crest elevations under bi-modal sea conditions

Figure 7 shows a similar pattern of results for the change in crest cut back with percentage and period of swell energy. The non-linearity is much more pronounced for percentage swell with the greatest change occurring up to 20%. Change with period appears to increase significantly between 14s and 19s.

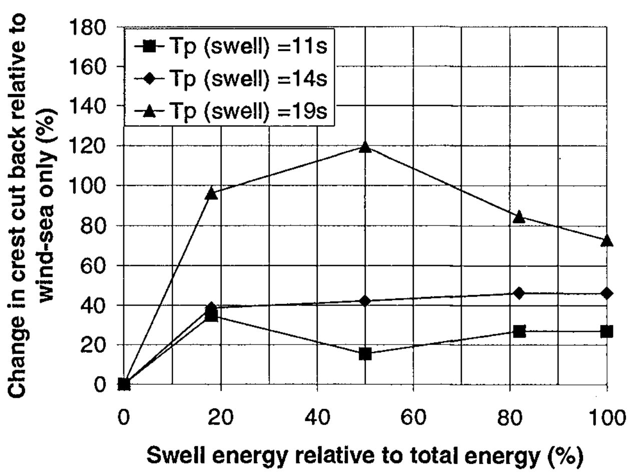

Figure 7 Relative shingle beach crest cut back under bi-modal sea conditions

These results confirm the field observation that relatively small levels of swell energy in combination with wind waves can cause greater beach response than an equal amount of energy in the wind sea only frequencies. This conclusion has importance in the design of shingle beach recharge schemes in those areas identified by the swell atlas as being subject to significant bi-modal wave conditions.

Other flume studies

A series of additional studies were undertaken in the wave flume to determine the importance of bi-modal wave conditions to structure design. Work concentrated on wave overtopping of simple sloping walls, but some tests of rock armour stability were also completed.

Overtopping tests considered seawall slopes of 1:2 and 1:4, foreshore slopes of 1:7, 1:10, 1:20 and 1:50, and crest freeboards of 2m and 4m. Wave conditions included those used for shingle beaches, plus some additional heights and periods to provide a larger data set for analysis.

Measured overtopping rates varied with each structural parameter and with wave conditions. Bi-modal and swell only waves were shown to be most significant for the 1:4 wall slope with a 4m freeboard. Foreshore slopes made little difference.

Figure 8 shows the results for a 1:50 approach slope. Unlike the beach response results discussed earlier, the overtopping curves tend to be linear, apart from an apparent steepening towards the 100% swell conditions.

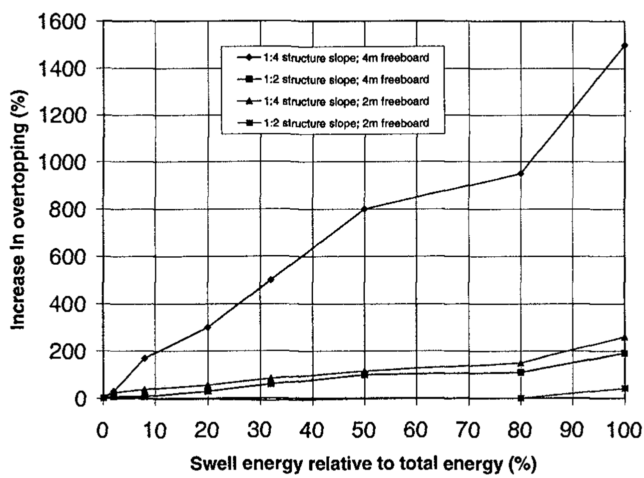

Figure 8 Relative change in overtopping rates under bi-modal sea conditions

The overtopping test programme showed conclusively that sloping seawall design should consider complex wave spectra in areas exposed to even moderate swell. Failure to do so could result in a significant underestimation of risks during storms.

A brief series of tests were run to determine the potential significance of bi-modal waves in determining armour rock stability. The damage results were inconclusive but suggested that complex sea states could be important to structural design.

Conclusions

The important influences of bi-modal wave conditions (combining wind sea with an underlying long period swell) have been observed in the field and in a large scale wave flume model. The probabilities of occurrence of these wave conditions around England and Wales have been estimated and published as part of a wave atlas (Hawkes, *et al*, 1997) .

These conditions are believed to be important to the design of shingle beach recharge schemes and to some coastal structures. As yet little work has been done on defining the physical processes involved in the interaction between complex sea conditions and beaches. The results of this study can be used by coastal engineers to improve beach design, but no formal design tools have yet been developed.

Acknowledgements

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