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Probabilistic modelling of long-term beach evolution near segmented shore-parallel breakwaters

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ABSTRACT

This paper presents a new framework for probabilistic modelling of long-term beach evolution in the vicinity of detached breakwaters. The study focuses on the key physical processes contributing to beach variability over a range of spatial and temporal scales. Based on a one-line model, the framework is enhanced with sophisticated solutions for beach-wave-structure interaction, diffraction together with a treatment of varying tide level. The sediment transport rate is calibrated at regional and local levels using data from bespoke field campaigns and site-specific coefficients are proposed. Monte Carlo simulation is conducted for long-term shoreline simulation under a sequence of time varying sequence of waves, currents and tidal levels. The results of the Monte Carlo simulation give an insight into the statistical characteristics of beach behaviour within the defence system. In particular, regions within the scheme that are relatively stable and those that exhibit greater natural fluctuations are identified.

1. Introduction

Shore-parallel breakwaters can provide an effective solution for coastline protection together with substantial recreational development. They have been successfully used to control shoreline evolution on many coastlines of the world, particularly in areas with a small tidal range. The use of shore-parallel breakwaters around the coast of Great Britain is limited to a few sites due to the lack of design and construction experience in a meso-tidal environment. The North Norfolk coastal village of Sea Palling is one such site where a shore-parallel breakwater scheme was implemented between 1993 and 1997. It is classified as a flood defence as its main purpose is to prevent sea flooding of the Norfolk Broads — a protected area of scientific interest. Although it has been recognized as a successful scheme (Fleming and Hamer, 2000), a full understanding of the sediment movements, the driving forces and their inherent variability has yet to be obtained. An understanding of, or at the least a means of quantifying, the range of beach movements likely to occur within and around the scheme over a period of a decade or so is of major importance to those attempting to manage this coast. As shore-parallel breakwater schemes continue to be considered as possible engineering solutions around the world a methodology that can assist in quantifying the variability of beach position in their vicinity provides a wider motivation for this study.

Within the last few decades there has been substantial interest in modelling the regional sediment transport and the performance of offshore breakwaters within the area (Vincent, 1979; Damgaard et al., 1999; Halcrow, 2001a,b; Pan et al., 2005; Bacon, 2005). These pioneering works analysed the possible causes of erosion by natural processes, i.e. action of waves and tides. However, the long-term effect of their time-dependent characteristics has been largely ignored. For the numerical study of long-term beach development it is certainly desirable that only key features are included, without the overhead of detailed process modelling. In this respect, the standard one-line model established by Pelnard-Considère (1956) is a prime candidate. The theory is based on the concepts that: there is continuity of sediment; sediment transport is predominantly wave-induced littoral drift; and the beach profile remains fixed, moving bodily seaward or landward as the shoreline accretes or erodes. Under the assumption of small angles the one-line model reduces to a diffusion-type equation. Analytical solutions to this equation have been derived for several different cases (e.g. Le Mèhauté and Soldate, 1977; Larson et al., 1987; Wind, 1990; Larson et al., 1997). These solutions make use of assumptions that the wave crests are approximately parallel to the shoreline and the prevailing wave conditions are spatially and temporally uniform. Analytical treatment of time varying wave conditions was introduced by Larson et al. (1997) for cases where the wave angle was a function of time. Dean and Dalrymple (2002) outlined a method for solving beach evolution for arbitrarily (time) varying wave conditions on an initially straight beach. More general solutions for time varying conditions, arbitrary initial condition and

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source terms have been presented by Reeve (2006) for a single groyne and by Zacharioudaki and Reeve (2008) for natural beaches and a groyne compartment.

Analytical treatments of the case where waves are arbitrary functions of space and time have yet to be developed. As a result, computational solutions are important as they do not have the limitations of analytical methods. These models solve the continuity, sediment transport and wave angle equations simultaneously, stepping forward in time (Gravens et al., 1991) and are well-suited for general engineering practice. Despite its simplicity, the one-line theory has been applied to complex modelling systems with arbitrary combinations and configurations of structures (Hanson and Kraus, 1989). Vrijling and Meyer (1992) applied the model to perform Monte Carlo simulations of the shoreline position near a port, and Dong and Chen (1999) included random temporal variability in a Monte Carlo study adapting the model to account for cross-shore sediment exchanges.

The utility of the Monte Carlo method is limited by the lack of sufficient contemporaneous oceanographic and shoreline position measurements. Wave conditions to drive the one-line model are normally available only as summary statistics. LeMéhauté and Soldate (1983) addressed the problem of using wave statistics and suggested a procedure for creating representative wave parameters. Due to highly nonlinear transport process, the cumulative effects of driving forces cannot be obtained from a wave rose such as found in climatological atlases. A different statistical approach is thus sought here. The procedure given by Cai et al. (2007) has been employed to generate numerous sequences of correlated wave conditions with the correct site-specific statistical characteristics.

One of the important aspects in the present study is an incorporation of tides although it is still a very elementary treatment. We have used a formula derived by Hanson et al. (2006) to explore the effect of tidal currents on sediment transport, while the varying tide levels are included by altering the water levels. Another complexity arises from the spatial variations of wave forces determined by the offshore structures. In recognizing the importance of diffraction from the multi-segmented shore-parallel breakwaters, a sophisticated wave model was employed to simulate wave transformation around the reefs under varying tidal levels and different angles of wave incidence. By introducing the numerical solution, an accurate description of the wave fields at the breaking point has been achieved.

This paper describes the extensions made to a one-line modelling framework to address the probabilistic modelling of the influence of multi-segmented shore-parallel structures on the shoreline evolution. A brief description of the site is given in Section 2. Following the explanation of model development in Sections 3, 4 presents the model calibration. Then, Monte Carlo simulation is described in Section 5. Finally, the main conclusions are summarised in Section 6.

2. The Sea Palling scheme

2.1. Overview

The coastline of East Anglia on the East Coast of England has experienced considerable erosion throughout history. An offshore reef system was built in Sea Palling as part of the regional coastal defence strategy to provide the best form of beach protection, whilst having the minimum impact on the longshore drift regime. An aerial view of the scheme is shown in Fig. 1.

The breakwaters were built in two phases. The north-western four breakwaters, numbered 5 to 8, were constructed first (Phase 1), followed by the five reefs 9 to 13 (Phase 2). Fig. 2 shows the general layout dimensions and phases of the nine breakwaters which comprise the project that was completed in 1997. A crest level of 3.0 m with reference to ODN was adopted for Reefs 5–8 based on the assessment of the structure transmission, which are surface-piercing at all states of the tide. The crest level was lowered by 1.7 m for breakwaters 9–12, so that they remain submerged during a MHWS tide; the breakwater length and gap width were also reduced. The most southeastern breakwater, Number 13, was designed with a crest level of −1.0 m, with the aim of reducing the effect of sediment starvation downdrift. Beach evolution occurred as soon as construction of the breakwaters began. Following the construction between 1993 and 1995, tidal tombolos developed behind Phase 1. Landward of the five reefs built during Phase 2, a sinuous shoreline has developed which continues to allow flow around the breakwater system at all states of the tides. In association with periodic nourishment programmes the scheme has been locally successful in retaining recharged sediment on the beach.

Fig. 1. Aerial photograph of the Sea Palling scheme, looking northwest, (courtesy of Mike Page).

2.2. Waves climate at Sea Palling

The frontage of Sea Palling is exposed to a wide range of wave directions, ranging from north-northwest to south-east. For our study we have used hindcast offshore wave conditions from the UK Meteorological Office European wave model at 53.00°N, 1.54°E. This point is just 30 km northwest of the site, with a mean water depth of 18 m. The data set consists of significant wave height H, period T and mean wave direction θ at 3 hourly intervals. The duration of the data set is from 31/12/1994 to 01/01/2008. Time series of H, T and θ considered herein are shown in Fig. 3. The significant wave height varies from 0.1 m to 3.9 m, while waves approach the beach from a wide range of directions.