Larger-scale morphodynamic impacts of segmented shore-parallel breakwaters on coasts and beaches: An overview of the LEACOAST2 project

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ABSTRACT

This paper presents an overview of the LEACOAST2 research project, studying the large-scale morphological impacts of nearshore flood defense structures (shore-parallel breakwaters) on coasts and beaches. The project uses a study site at Sea Palling, Norfolk, UK, where nine segmented shore-parallel breakwaters are present, to conduct detailed field measurements, regularly bathymetric surveys, and long-term remote-sensing monitoring. Both process-based and probabilistic models are applied to the site to investigate the beach response to the nearshore structures for short-term storm conditions and longer-term macro-tidal conditions. The paper also highlights the key findings obtained from the project.

ADDITIONAL KEYWORDS: Shore-parallel breakwaters, beach morphology, macro-tides, morphological modelling, one-line model, sea palling, X-band radar, Argus video system

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Coastal structures, such as segmented shore-parallel breakwaters (SSPB), have been used worldwide for coastal defense. UK schemes include the breakwaters at Kings Parade in Wirral, Elmer in Sussex and Sea Palling in Norfolk. Most current UK structures were designed a decade or more ago with the object of providing appropriate levels of flood protection as well as resisting the worst storm conditions likely to be experienced over the lifetime of the structures and minimizing the long-term (25-50 years) impact of the structures on adjacent coastlines. However, existing UK design guidelines rely heavily on micro-tidal experience (Pope and Dean 1986), and even this experience is imperfect as demonstrated by the removal of structures in the U.S. and the use of modern computer methods, which show the inability of some engineering criteria to correctly predict the formation of salients and tombolos in the lee of such structures (O'Connor *et al.* 1995). Recently, the significance of impacts of increased future flood risk with some 4 million people and properties in England and Wales alone under threat and a potential increase in flooding costs by a factor of 20 has been highlighted in the Foresight Project led by the UK Government's Office of Science and Technology. While much is being done, there is an urgent need for further action as regards the use of such structures and particularly their long-term impact.

In the past decades, design procedures made extensive use of computer modelling techniques to assess both hydrodynamic and beach level change (Hamer *et al.* 1998; Fleming and Hamer 2000). For storm-scale changes, intra-wave or wave-period-averaged models of wave and current climate are used and linked to morphological modules to predicate beach level change. Much international research effort has also been put into improving and evaluating such model approaches, particularly for open beach situations, and usually in micro and meso-tidal conditions (Zyserman *et al.* 1998; Soulsby 2000; O'Connor *et al.* 2000). The majority of such work has also been confined to use of a single representative wave and tide condition, and sand size for the bed material. It is also usually restricted to a few final design layouts because of limitations on computer time and cost. Although physical models can also greatly help the design process, there are also limitations (Ilic *et al.* 1999), particularly for the UK conditions.

For medium-term predictions, covering up to 10 years of beach change, two different approaches have been used. Firstly, in an attempt to retain much of the complexity of interacting beach processes, process-based "storm-scale" models are used in various ways in an attempt to reduce calculation times (De Vriend *et al.* 1993; Nicholson *et al.* 1997). Such "aggregation" approaches often look for an

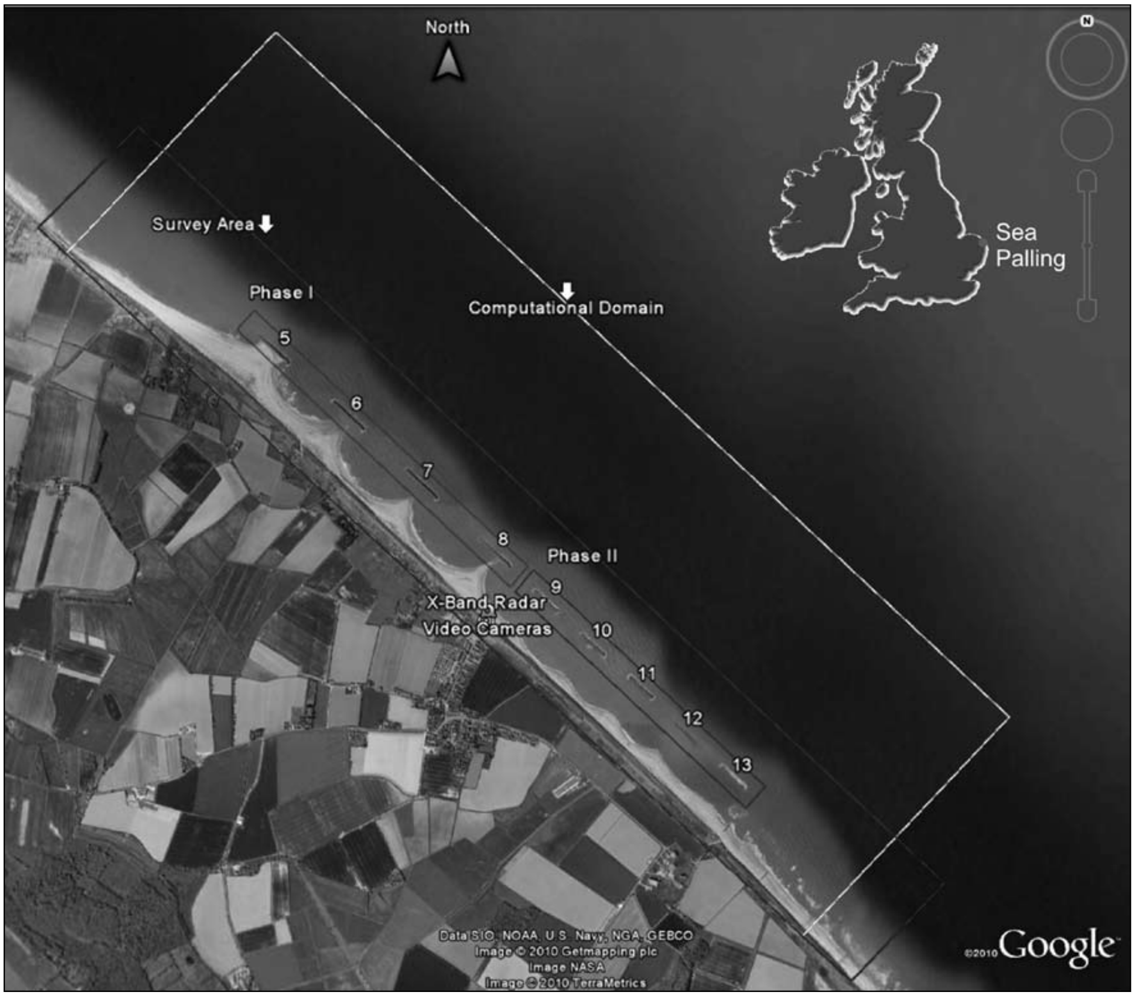


Figure 1. Location of the study area and breakwaters at Sea Palling, Norfolk, UK.

"average" tide to represent spring-neap cycles. In other cases, particular physical processes are neglected, as for example wave overtopping, structure porosity, tidal water level change, and use is made of a single beach grain size. Nevertheless, use of such models to study medium term (one-year) changes at the Sea Palling site have shown encouraging results while also highlighting areas of lack of agreement with beach bathymetry (Hall and Damgaard 2000). The second approach removes most of the detailed interactive processes and describes the beach dynamics with a simple 1-line or n-line model (Perlin and Dean 1993). Both the distribution of the long-shore sediment transport quantities and the equilibrium shape of the beach are often based on the American coastal conditions of medium sized sand with little tidal influence. Such models are very computer efficient and have been modified to include the effect of diffraction of breaking waves by near-shore structures and shown to give realistic results in microtidal conditions, such as GENESIS (Hanson and Kraus 1989). When additional processes such as the wave and flow transmission through the porous structures with mixed sediment beaches are considered, the situations are more difficult to predict (Pan *et al.* 2004).

For long-term (25-100 year) simulations it is desirable that only key features are included in order to avoid the overhead of detailed process modelling. In this respect, the one-line beach shape model originated by Pelnard-Considere (1956) is a prime candidate. Analytical treatment of time-varying wave approach angle was introduced by Larson *et al.* (1997), while 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 source terms have been presented for a single groin (Reeve 2006) and for natural beaches and a groin compartment (Zacharioudaki and Reeve 2008). Analytical treatments of the case where waves are arbitrary functions of space and time have yet to be developed. Despite its simplicity, the one-line theory has been applied with reasonable success to complex modelling systems with arbitrary combinations and configurations of structures (Ozasa and Brampton 1980; Hanson *et al.* 1998).

Field data, which is required for the design process, is often sparse in both space and time. In previous studies, most bathymetric data are only available over the inter-tidal area and are often collected at widely different times to those for the sub-tidal zone, which is not yet satisfactory for model set-up, particularly if process-based approaches are being used. Such data gathering and databases can be improved significantly in the future by use of the latest state-of-the art remote-sensing monitoring equipment. Major EU projects, such as COAST3D (Soulsby 2000) and INDIA (O'Connor *et al.* 2000), have demonstrated the advantages in using video, acoustic and radar technologies to monitor the open beach environment during storm action and over the medium term. The applications of these techniques to situations with structures has been done under the EU-supported COASTVIEW Project (Davidson *et al.*

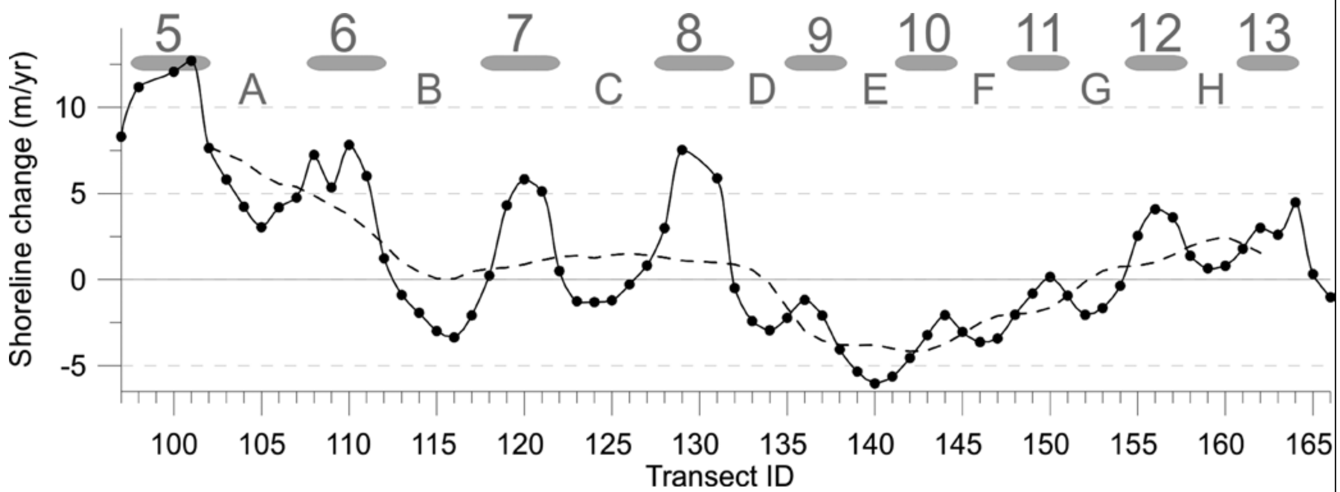


Figure 2. Medium-term (1991-2005) rate of shoreline change. Transect spacing is 50 m. The dashed line is a 500 m running mean.

2006), but further work on the integrated use of video, radar and acoustic equipment is also needed, particularly in the presence of coastal structures.

In addition to the design limitations of existing knowledge and the lack of integrated data, there is also a need to better understand the complexity of the sediment trapping processes of groups of near-shore breakwaters, particularly in macrotidal conditions, when both natural and artificial sediment sources can be present. Use of process-based morphological models combined with field measurements can help to unravel the complexity of such sediment transport pathways and can thereby improve estimates of future long-term recharge needs as well as the best phasing for the use of non-native materials along with the likely consequences of removing natural sources as, for example, by the protection of adjacent eroding cliffs to facilitate the planning of new industrial or urban development or the extension of existing ones.

To this end, the LEACOAST2 project was proposed jointly by the Universities of Plymouth, Liverpool and East Anglia, in collaboration with Proudman Oceanographic Laboratory (POL), HR Wallingford, Halcrow Group and the Department for Environment, Food and Rural Affairs (DEFRA)/the Environment Agency (EA) and funded by the UK Engineering and Physical Sciences Research Council (EPSRC) to address the knowledge gaps identified above, so that enhanced design tools and integrated monitoring approaches can be further developed to assist future engineering studies and coastal planning projects. This project was also accompanied by a parallel research project (CSG7) funded by DEFRA/EA for additional information to be gathered and analyzed (Johnson *et al.* 2010) for improving the design guidelines. The LEACOAST2 project built upon an earlier research project (LEACOAST) at the same site also funded by the EPSRC, with much extended study area, computer modelling and field work. The LEACOAST project was focused on the morphological response of a particular representative SSPB embayment under storm conditions (Bacon *et al.* 2004; Dolphin *et al.* 2004, Pan *et al.* 2005).

This paper gives an overview of the LEACOAST2 project and the methodology used in the project, and highlights the key findings from the project. Further details on these findings can be found in the relevant papers referenced and the project website: <http://www.research.plymouth.ac.uk/cerg/leacoast2>.

METHODOLOGY

The main objective of this research project is to evaluate the generic effect of shore-parallel breakwaters in macro-tidal conditions on coastal morphology over a spatial scale of kilometers and a temporal scale of months to years, with a combination of field measurements during the storm events, long-term remote-sensing monitoring, regular beach and bathymetric surveys, as well as deterministic and probabilistic morphological modeling. The results from the project are also used for further analysis in a parallel project undertaken by the industrial partners funded by DEFRA/EA to improve the current design guidelines. To achieve the research objective, the project makes use of an extensive database which has been built up for the site near the village of Sea Palling on the Norfolk coastline of the UK from previous research. The breakwater scheme, which has been in operation for some 15 years, was built after the severe flooding to the area in 1953 and subsequent storm surge events. It consists of our surface-piercing breakwaters (high-crested) and five overtopped breakwaters (low-crested) built in two phases (Phase I and Phase II), as shown in Figure 1. Whilst Reefs 1-4 were designed, but never built, the high-crested breakwaters built in Phase I (Reefs 5-8) are longer and more widely spaced in comparison with the low-crested breakwaters built in Phase II (Reefs 9-13). The modifications to the Phase II breakwaters were due to the rapid morphological changes following the construction of the Phase I breakwaters. The crest level of high-crested breakwaters (Reefs 5-8) is approximately 2.5 m above the mean sea level (MSL), and that of the low-crested breakwaters (Reefs 9-12) is approximately 1 m above MSL. Reef 13, the lowest breakwater within the scheme, has its crest level approximately 1 m below MSL. The particular configuration of the breakwater scheme at the study area significantly complicates the hydrodynamics and morphodynamics adjacent to the breakwaters, but presents high scientific significance for the research. The maximum spring tidal range at the site can be up to 4.5 m. The waves are predominately northerly and northeasterly. The surge level during the severe storms can be more than 2 m.

The study area of the project covers a 6-km-long stretch of coastline, consisting of four sub-regions: 1) an up-drift zone from Cart Gap to the first breakwater; 2) the four high-crested SSPBs; 3) five low-crested SSPBs; and 4) the down-drift zone as far as Horsey. On a time scale of months to years, in general, the SSPBs cannot be viewed in isolation from the beaches and up/down-drift. Evidence is accumulating of: 1) the steady evolution of the northern embayments, indicating that a dynamic-equilibrium has yet to be reached; 2) rapid beach recovery from storms; and 3) the tidal current regime as a significant factor in moving sediment through the Phase 1 SSPBs. However, evidence is still lacking on the overall sediment transport pathways around the system, which is particularly a crucial issue of bypassing and loss of sand to the lower shoreface, of the interaction of the SSPBs with the up- and down-drift beaches and the exchange of sand between the four sub-regions. All are essential for understanding the longer-term, regional context and for developing generic guidelines that can be applied to future design of SSPBs in UK and other macrotidal waters.

In order to achieve a better understanding of the sediment transport pathway, and interactions between the structures and tides/waves on longer temporal and larger spatial scales, the research methods employed in the project are described in the following sections.

FIELD MEASUREMENTS

Large -scale field surveys of beaches and bathymetry were conducted at monthly intervals between October 2005 and September 2007 from Cart Gap to Horsey (~5 km out to ~10 m below MSL) by the University of East Anglia (UEA) to provide details on morphological variability and context for the process measurements and modelling studies. Two shorter process campaigns were conducted during April-May 2006 and October 2006-January 2007 by Proudman Oceanographic Laboratory (POL), which is now part of the UK National Oceanography Centre (NOC), and UEA. The process studies include the measurements of hydrodynamics, sediment concentrations, particle size, and bedforms using tripod frames at various locations in the vicinity of the breakwaters. New marine acoustic instrumentation, developed in the UK over the last few years, were used to make direct measurements of the sediment transport, bedforms and associated hydrodynamic forcing parameters at a number of points located both within the SSPB system and just outside the SSPBs in the region where sand bypassing of the system may be occurring. High-frequency acoustic backscatter instruments (ABS) measured the suspended sand concentration at intrawave timescales, while acoustic Doppler systems profiled the water column and measure turbulent intensities and stresses. Rotary and linear acoustic scanners were used to measure bedforms and bedform migration rates at the same time (essential for the estimation of bedload transport). Tripods were specifically designed to withstand the extreme forces on the frames and instruments during the storm conditions. Deployment of the instrument frames was a critical part of the field measurement, and was also the most hazardous. The offshore frames were deployed and recovered by a boat and the nearshore frames were deployed by the tractor and lifting machinery and man-handling.

REMOTE SENSING MONITORING

For the LEACOAST2 project, a five-camera video system (Argus) operated by the University of Plymouth (UP) team, was used to resolve changes in beach and intertidal morphology at daily, storm event, and seasonal timescales. Combining the video data from Argus with regular beach and bathymetry surveys, and the extensive archive of survey data already available for the site from the LEACOAST project and EA, made it possible to study the long-term (>10 years) variability of the system. The long time-series, spatial coverage, and temporal resolution of the video-derived morphology has also permitted a statistical analysis of the degree of variability of the defended coastline in terms of shoreline behavior and salient dimensions. Shoreline time-series were analyzed using Empirical Orthogonal Functions (EOF) to establish the dominant time and length scales of coastal change (Fairley *et al.* 2009). This built on work conducted within the European CoastView project by investigating new Coastal State Indicators (CSIs) that helped coastal managers to monitor and manage coastlines defended by SSPB (Davidson *et al.* 2007). Video-derived CSIs are parameters that allow coastal managers to monitor the 'health' of the environment and will give a clear indication of when management intervention is required. This was the first deployment of a coastal video monitoring system on a mixed beach defended by SSPBs. CSIs include parameters that allow the daily calculation of beach width, inter-tidal beach volume, and maximum tolerable salient formation, which help the coastal manager to monitor the integrity of the beach and provide guidance on when to initiate coastal defense procedures (e.g. sediment recharge), for example when beach volumes fall below threshold values. Appropriate threshold values will be variations that are over and above the natural (e.g. seasonal) variability of the system which may result in failure of the defense and loss of the value or function of the coast. These benchmark values were established in part via the application of EOF analysis of the video-derived data. In addition to providing valuable insight into the morphodynamics of beaches defended by SSPBs, the video-derived system will also provide essential boundary conditions and validation data sets for the numerical modelling.

During the LEACOAST2 project, a shore-mounted X-band radar, which provides 24-hour images of the waves on the sea surface by the backscatter of radio waves with a resolution of ~10 m out to a range of ~2 km, was installed and operated by POL. As has been demonstrated (Wolf and Bell 2001), the marine X-band radar can be used with appropriate digital recording systems to provide the required image sequences for wave spectra and bathymetric inversions. Both linear and nonlinear wave theories can be used to produce a depth inversion algorithm (Bell *et al.* 2004). This allows subtidal bathymetry to be retrieved out to depths of about 20m.

NUMERICAL MODELLING

Both process-based and probabilistic modelling techniques were employed in the project to achieve a better understanding of the impact of structures on the adjacent beaches under the short-term (storm) conditions with detailed nearshore processes and longer term (years) impact on shoreline changes. By

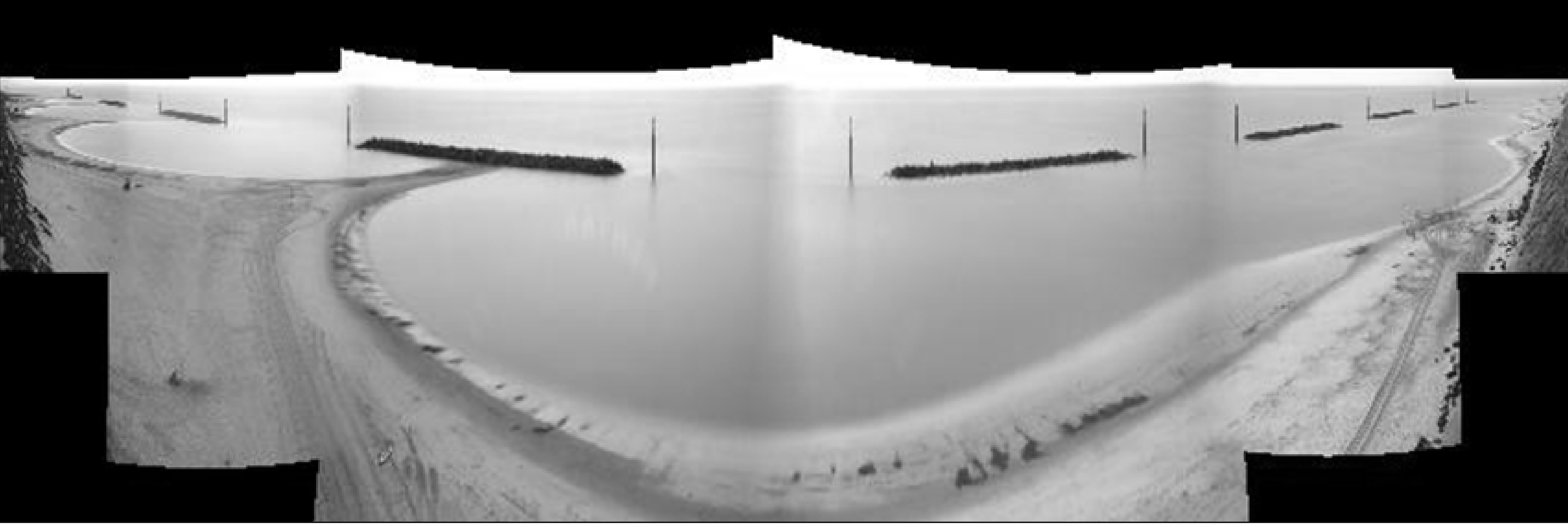
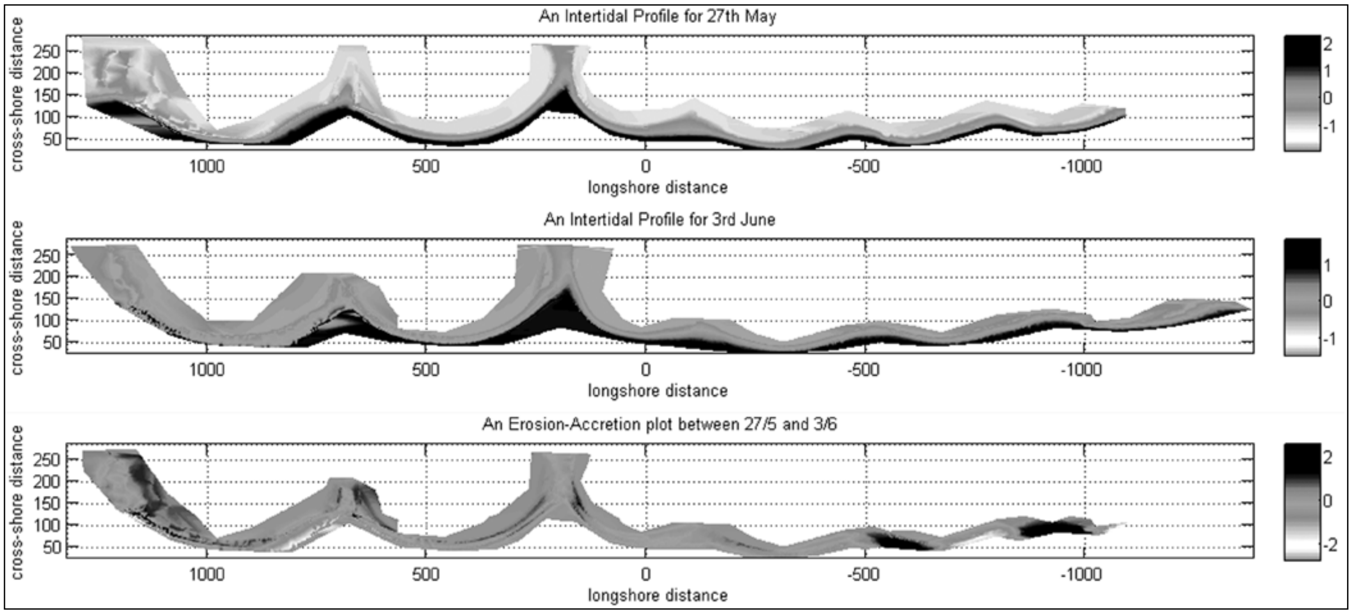


Figure 3. (a, above) Combined video image from Argus; (b, below) Rectified bathymetries and the bed level changes derived from video images.



combining both numerical modelling approaches, the long-term coastline evolution can be adequately predicted with short-term processes being appropriately parameterized or simplified.

The existing 2D process model, which has been developed within a number of previous research projects (O'Connor *et al.* 2001; Pan *et al.* 2005), was further developed in the project to include additional processes of specific importance at this study site, such as wave overtopping (Du *et al.* 2010) and mixed sediments. The model was operated in a fully dynamic mode to account for the interactions between nearshore waves, tides, sediment transport and the morphological changes, forced by time-varying wave and tide conditions. This "total" process model (TPM) was tested against existing large- scale laboratory data (Cáceres *et al.* 2008), wave, tide, sediment, and bathymetric data from the earlier LEACOAST project, and also against the newly acquired LEACOAST2 data acquired within the project.

For modelling longer-term and large-scale beach response to coastal schemes, probabilistic approaches have been commonly used. For example, Vrijling and Meyer (1992) performed Monte Carlo simulations of the shoreline position near a port, and Dong and Chen (1999) reported a Monte Carlo study in which a one-line model had been adapted to account for cross-shore sediment exchanges. Although showing how probabilistic approaches could be used in beach prediction both these studies made quite drastic assumptions about the statistics of the wave conditions and the beach response to these. Wang and Reeve (2010) developed a rigorous approach that incorporated the procedure of Cai (2007) to generate sequences of correlated wave conditions with the correct site-specific statistical characteristics. Further, the one-line model was dynamically linked to an elliptic mild-slope equation (Li *et al.* 1993) that allowed the wave propagation in the nearshore and within the detached breakwater scheme to be accurately represented.

Both modelling approaches were integrated, with the results of the process-based model assisting the parameterization of the longshore currents and sediment transport rates for the multi-line probabilistic model.

RESULTS

The project generated large volume of unique and valuable data sets, which are managed and distributed by the British Oceanographic Data Centre (BODC: www.bodc.ac.uk). While the detailed results from this project are presented in individual papers given in the references, the key findings of the project are highlighted here.

CURRENTS, WAVES, AND SEDIMENTS

Current, wave, tidal level, and sediment transport measurements were mainly concentrated on the area of Phase II breakwaters, with few also on the area of Phase I breakwaters in order to provide comparable data to those collected in the LEACOAST project. Field measurements were conducted in two stages: the first stage covers a period of 6 weeks from 25 March 2006 to 5 May 2006. This was regarded as the pilot exercise for the main campaign, and proved the logistics of deploying and recovering the instrument frames. The second stage was the main campaign, carrying out two 6-week back-to-back deployments from October 2006 to January 2007. Sector scanners captured the detailed information of the bed level changes at the measurement location, as well as the ripple characteristics. The measured velocities from the second stage campaign from the measurement frame close to Reef 5 clearly indicate the significant differences between flood and ebb phases due to the tides. For spring tides, the velocity during flood phase can be twice that during ebb phase. The sediment concentrations measured by the ABS show even larger asymmetry. The information forms an important and unique part of the database for process and micro-model calibrations.

BATHYMETRY AND BEACH MORPHOLOGY

Monthly beach and bathymetry surveys were conducted over all four subregions (including the region covered by the LEACOAST project so as to extend the medium term database), supplemented with storm-response surveying during the intensive field campaigns. Using a second GRP-Rover and two GPS-sonar-systems allowed the beach and bathymetry to be surveyed concurrently and the entire area covered in two days. The unique beach and bathymetric survey data is extremely useful, not only for the model developments, but also for analysis and validation of remote sensing data and conceptualization of sediment pathway in the complex system.

As shown in Figure 2, the persistent spatial pattern in the shoreline rate-of-change is of alternating local maxima and minima associated with breakwaters (tombolos or salients) and breakwater gaps (embayments). The gap-to-tombolo differences are large for Phase I breakwaters (4.8-9.7 m/yr), especially Bay B, whilst for Phase II breakwaters the gap-to-salient difference rates are smaller (0.7-3.7 m/yr). These differences reflect formation of the wider tidal-tombolos for Phase I breakwaters (250 m wide) and the more subdued salients (75-95 m wide) for Phase II breakwaters. A 500-m running mean, corresponding to the length scale of a Phase I breakwater and gap (red dashed line), highlights the broad spatial pattern of accreting shorelines at either end of the system and a global minimum in the center (-6.03 m/yr in Bay E) near the junction between the Phase I and Phase II breakwaters. Both embayments and tombolos/salients follow the trend of decreasing accretion to increasing erosion toward Bay E near the center of the breakwater system. The lower beach width toward the centre of the system suggests littoral drift of sediments showing a continued sediment deficit with insufficient sand reaching the centre of the breakwater system. Wider, accreting beaches at either end of the system trap and retain some of the sediment moving alongshore during individual storm events as it encounters the breakwater system. As the net littoral drift is from the north (Vincent 1979), wider beaches have formed at the north end. The higher breakwaters in the north are also responsible for the wider beaches there. However very little sediment gets through the breakwater system; just south of the SSPBs (beyond Reef 13) beach levels have dropped to such an extent that beach recharges of 400,000 m^3 and 850,000 m^3 were required in 2000 and 2003-4 along a 2 km frontage.

VIDEO REMOTE SENSING

An array of five video cameras was installed on a purpose built tower 26 m above mean sea level in the central position of the study area, see Figure 1. The cameras captured images of the embayments of both Phase I and Phase II breakwaters, overlapping the area covered by the X-band radar and the regions in which the hydro-sedimentological measurements were made. The video provided a near-continuous day-light time series of images that have facilitated a quantitative assessment of the evolving morphology in relation to storms, anthropogenic effects (e.g. sediment recharge) and seasonal changes.

This system provides a unique opportunity to apply currently evolving algorithms for the extraction of hydrodynamic parameters from video data. For example, using rapidly sampled images, wave overtopping characteristics were quantified from the video images. Analysis of these pixel collections allowed the amount of overtopping and type of transmitted waves to be investigated. A critical value of relative freeboard for the onset of overtopping of this type of structure was determined (Fairley *et al.* 2007). The video system is able to provide valuable insight into wave refraction/diffraction and current circulation leeward of the offshore breakwater systems on a scale comparable to the numerical models. These measurements provided insight into sediment transport pathways around the SSPBs. Figure 3(a) shows the combined image from all five cameras covering the entire study area. Analysis of the rectified video images led to the detailed bed level changes for a specific duration, as shown in Figure 3(b).

EOF analysis was used to decompose a video derived shoreline dataset into the dominant modes of shoreline change for both schemes. The newly-introduced manifestation of hydrodynamic parameters: the cumulative integral of the demeaned parameters, enabled the meaningful correlation of the temporal EOF components with forcing parameters and identification of the important influence of the tide on observed morphodynamic change to be obtained from the measurements. The results illustrate clear differences of the shoreline responses to the high-crested and low-crested breakwaters and variation in longshore sediment supply (Fairley *et al.* 2009).

X-BAND RADAR

An X-band marine radar was deployed on the roof of the Lifeboat shed, next to the tower for the video system. The system has a range of several kilometers, extending beyond all breakwaters in the site. Raw data were recorded automatically at least once per hour, and the radar images provide the directions of incident waves with spatial distributions. When sufficient wave conditions are present, post-processing can generate water depth maps, revealing the large bed features and their migration. Further process of the radar data also generates the current vectors in the area, which is an important supplement to the point measurements.

The comparison between the computed waves and the X-band radar measurements match well over the study area (Pan *et al.* 2007). Further data processing is still on-going, the preliminary results reveal unique and interesting features of currents and bathymetry in the area.

PROCESS-BASED MODELING

The existing 2D storm-scale model was further developed to include additional coastal processes. The effect of wave overtopping was identified as one of these processes. The model also has been optimized to allow for longer-term, up to a month, predictions. The process model covers the study site with a computational domain of 5 km in the longshore direction and 1.5 km in the cross-shore direction as shown in Figure 1. The grid size is 25 m by 12.5 m in the longshore and cross-shore directions respectively. Model tests were carried out with different wave, tide, and surge conditions, focused on the storm events in November 2006.

Figure 4 shows the effect of wave overtopping on currents in two embayments between Reefs 5, 6, and 7 at high water slack during the storm period. In the gap of the embayment the currents have been considerably enhanced by wave overtopping of the breakwaters. The longshore velocities in the lee side of the breakwaters have also been significantly altered, which will consequently impact sediment transport in the nearshore area. The detailed quantification of the impacts of wave overtopping on nearshore hydrodynamics and morphodynamics can be found in Du *et al.* (2010). Comparisons of the computed bed level changes with wave overtopping effects, with the measurements along a number of the cross-shore transects, show a good agreement.

PROBABILISTIC MODELING

For probabilistic modelling, a nearshore wave transformation model was dynamically linked to a one-line beach model. It takes into account wave overtopping of the detached breakwaters and was calibrated initially with the results from the process-based model. Wang and Reeve (2010) discuss the formulation and calibration of the model in more detail. In this study, we used hindcast offshore wave conditions from the UK Meteorological Office European wave model at 53.00ºN, 1.54ºE, approximately 30 km northwest of the site in a mean water depth of 18 m. The data set consists of significant wave height, mean zero-crossing period and mean wave direction at 3 hourly intervals during 31 December 1994 and 1 January 2008. With this 13-year sequence, using procedure of Cai (2007), 200 sequences of wave records, each of 13 years duration were generated. Each sequence replicates the marginal and joint distributions of the original sequence but provides a range of alternative but feasible sequences of wave conditions. Running the beach model repeatedly with each one of the 200 13-year realizations provides alternative (but statistically valid) sequences of beach response. The ensemble of results are used firstly to validate the Monte Carlo predictions of the positions of the bays and salients against beach surveys taken during the course of the project (covering a period

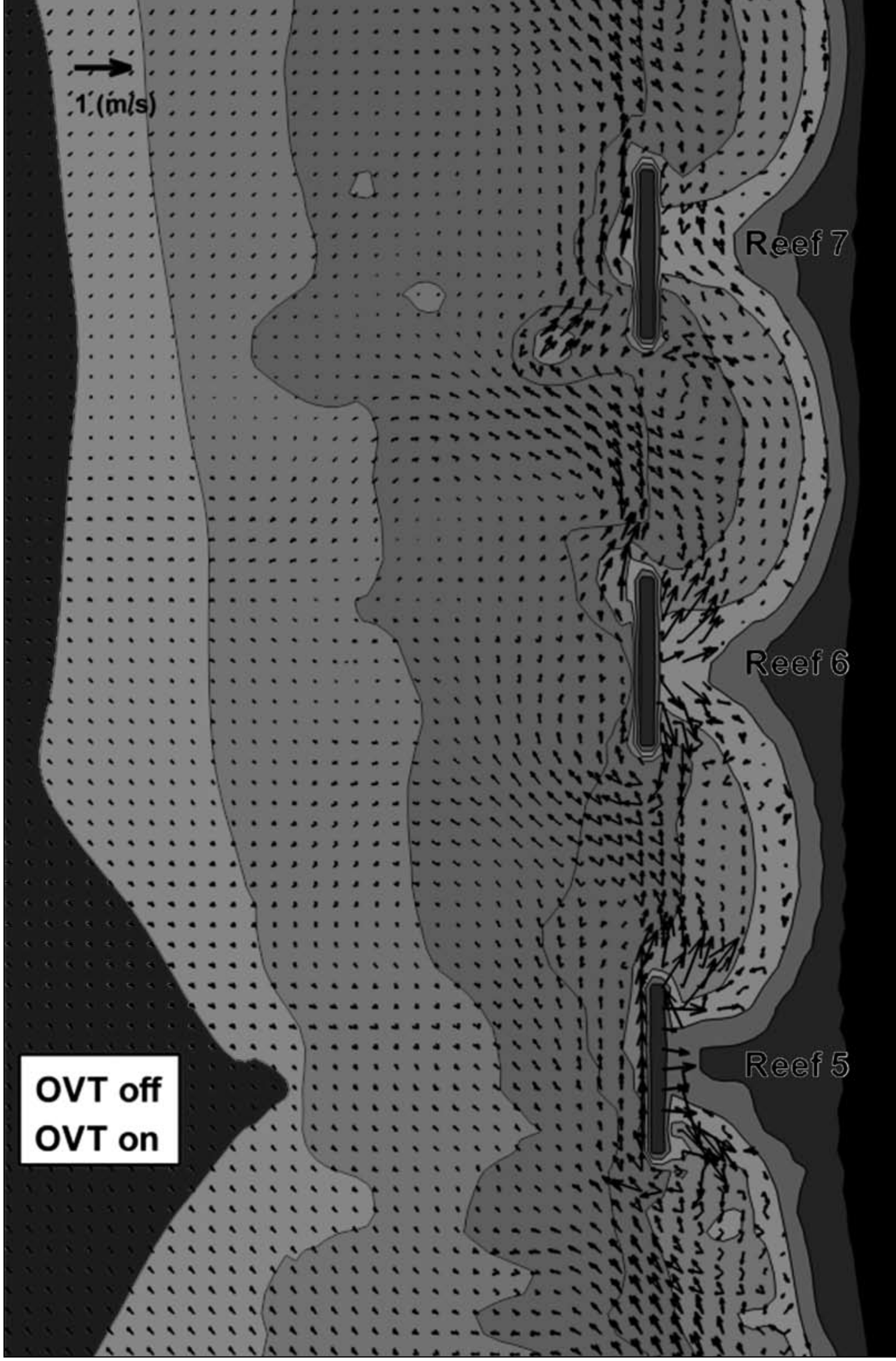


Figure 4. Effect of wave overtopping on hydrodynamics.

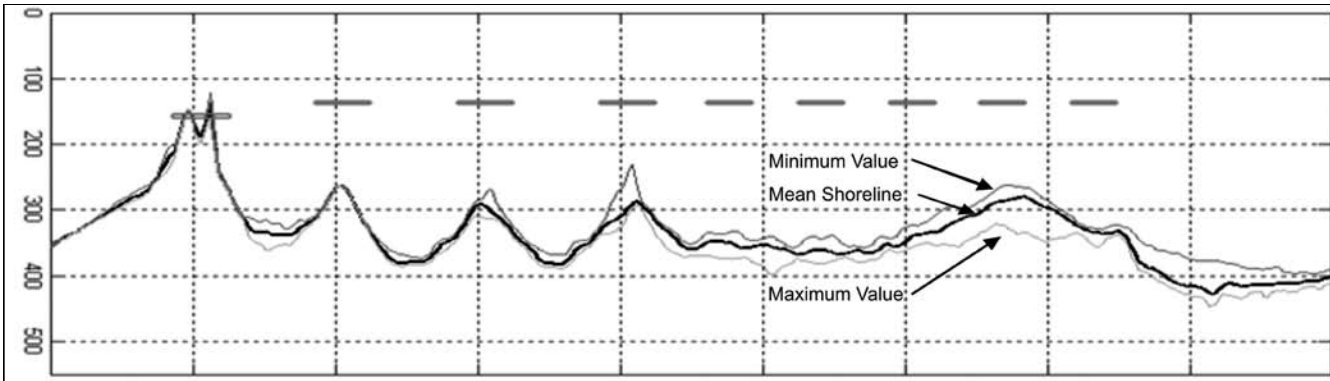


Figure 5. Predicted mean shoreline and its minimum and maximum values from 2-line model.

of ~six years), and then to investigate the statistics of beach position throughout the scheme. Calculated from the ensemble average statistics of the beach position as a function of time, the envelope of shoreline movement is shown in Figure 5. The results indicate that the tombolos and salients in the Phase I breakwaters are stable and the embayments and salients in Phase II are more variable. The shoreline position varies within a range of about 40 m, which coincides with a qualitative assessment of scheme performance from surveys.

CONCLUSIONS

The LEACOAST2 project combines regular field surveys, short-term process-scale measurements , long-term remote sensing monitoring, and advanced numerical modelling to study the impacts of the shore-parallel breakwaters on the coastal morphology, applied to the breakwater scheme at Sea Palling. The field measurements were well planned and executed and long-term monitoring was successfully carried out. The numerical models were developed to include key coastal processes. The project reveals great details of hydrodynamics and morphodynamics generically and systematically in such a dynamic and complex system. The unique database built from the field measurements, together with the models developed within the project, will be extremely useful to help in better understanding the interactions between waves, tides, and nearshore structures, as well as the resulting morphological changes. The project also provides detailed information and insights into the complex nearshore processes for coastal engineers to improve further the design of similar defense structures and overall coastal zone management. The key findings from the project are summarized as follows:

1) The field measurements indicate the significant impacts of macro-tides on the sediment transport pathway. The high water level during flood-tide and low water level during ebb-tide significantly alter the flow circulations, hence the sediment transport pattern. The rapid formation of tombolos after the construction of Phase I breakwaters clearly indicates the enhanced sediment transport due to the tidal effects, in comparison with the design criteria given by Pope and Dean (1986).

2) Long-term bathymetry surveys indicate that the high-crested breakwaters (Phase I) have resulted in larger yearly shoreline changes, ~6 m/year for the formation of salients/tambolos and ~2.5 m/year for the embayments. In contrast, the formation of salients and embayments is much slower for the low-crested breakwaters (Phase II). The interaction between Phase I and Phase II breakwaters has resulted in a complex shoreline change pattern in the inter-connecting area, which plays an important role in long-term shoreline evolution.

3) The remote-sensing monitoring techniques and the process algorithms developed from the project are demonstrated as powerful tools for studying long-term coastal hydrodynamics and morphodynamcs.

4) The process model results show that wave overtopping has significant impacts on the currents and waves in the embayments and the adjacent area of the breakwaters, and consequently on the morphological changes. Including the effects of wave overtopping in the process model is particularly important for the complex breakwater scheme at Sea Palling. The enhanced flow and sediment transport in the lee side of the breakwaters due to wave overtopping will likely slow down the formation of tombolos.

5) Statistics obtained from the probabilistic model shows the long-term variability of shoreline positions. The shoreline behind the Phase I breakwaters is predicted to be more stable than that behind the Phase II breakwaters, with Bay A being highly variable in its depth. The shoreline behind the Phase II breakwaters is predicted to have significantly more variability. Analysis of the distribution of the positions of shoreline over time has shown a definite asymmetry in several bays, which is an important behavioral fact for coastal managers to consider. Erosion to the downdrift area of the Phase II breakwaters, which is being protected by groins, appears more likely to occur in the future. However, thanks to the macro-tidal range at the site, the downdrift structures are found to have little effect on the breakwater system.

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