Journal of Coastal Research	SI 50	369 - 373	ICS2007 (Proceedings)	Australia	ISSN 0749.0208

Shore-parallel breakwaters in meso-tidal conditions: tidal controls on sediment transport and their longer term, regional impacts at Sea Palling, UK.

J.C. Bacon†, C.E. Vincent†, T.J. Dolphin†, J.A Taylor†, S-Q Pan‡ and B.A. O'Connor‡

†School of Environmental Sciences
University of East Anglia, Norwich
NR4 7TJ, UK.
John.Bacon@uea.ac.uk

‡Department of Civil Engineering
University of Liverpool, Liverpool
L69 3BX, UK.

ABSTRACT

BACON, J.C., VINCENT, C.E., DOLPHIN, T.J., TAYLOR J.A., PAN, S-Q. AND O'CONNOR, B.A., 2007. Shore-parallel breakwaters in meso-tidal conditions: tidal controls on sediment transport and their longer term, regional impacts at Sea Palling, UK. SI 50 (Proceedings of the 9th International Coastal Symposium), 369 – 373. Gold Coast, Australia, ISSN 0749.0208

Shore-parallel breakwater systems built in meso-tidal conditions display a more complicated morphological response than predicted by existing models and their impact on coastlines in the longer term (10-20 years) is unclear. The shore-parallel breakwaters at Sea Palling, UK, built to protect low-lying land from inundation, comprises four surface-piercing and five overtopping breakwaters, spanning a 4.0km length of coast. Earlier studies of the impacts of these breakwaters considered the impacts of waves but neglected the influence of the strong asymmetric tidal currents. TELEMAC was used to simulate tidal currents and elevations around the breakwaters, focussing on sediment transport over the tidal tombolos behind the four, northern-most (updrift) breakwaters; a small amount of wave-stirring (H_s=0.5m) was also included. The model suggests that the asymmetric tidal currents transport ~40,000 m^3 of sand through the system annually, around 20% of the pre-breakwater longshore transport rate.

Measurements of waves, near-bed currents, suspended sediment concentrations and bedform structures enabled verification of modelled sand transport rates (within 50%). RTK-GPS surveys provided high resolution topography and bathymetry of the beach, tombolo and nearshore seafloor; the rate and direction of tombolo movement from the surveys was also consistent with the modelled transport rates.

In addition to the tidally-driven transport, storms drive sand through the breakwater system but erosion of beaches down-drift indicates that the sand supply here is much reduced. Beach and bathymetric surveys over the 10 years since the breakwaters' construction show sand continuing to accumulate at the northern end of the breakwaters but that sand in the longshore transport is also bypassing and accumulating offshore of the breakwaters.

ADDITIONAL INDEX WORDS: *Morphology, Tidal Currents, Modelling, Telemac, Tombolo*

INTRODUCTION

The nine-segment, shore-parallel breakwater system at Sea Palling, Norfolk, UK. was built in two phases between 1994-97. It forms an important component of the coastal defence in the 14km coastal cell between Happisburgh and Winterton. The structures were designed to attenuate storm-generated waves, often enhanced by storm surge conditions, to protect the beach which is backed by a sea wall and a single sand dune. These in turn protect 60 km^2 of high-grade but low-lying, agricultural hinterland (THOMALLA and VINCENT, 2004). Their location in relation to the UK is shown in Figure 1.

The Sea Palling breakwater system ranks as one of the largest of its type (LAMBERTI et al, 2005) although the meso-tidal conditions and open storm-affected coastline have resulted in a significantly different morphological response. The design relationships between breakwater-length, gap-length and distance off-shore used for predicting beach morphodynamic response to the breakwaters at Sea Palling were developed at sites with more sheltered environments. The breakwater dimensions used for the first four (surface-piercing) breakwaters at Sea Palling (Phase 1) predicted the formation of salients. Gap erosion occurred and tidal-tombolos formed; at low-water the tombolos are fully emergent and effectively blocked the longshore sand transport. Inside the five, Phase 2, overtopping breakwaters built to the southeast, revised parameters were used for the final five breakwaters built in Phase 2; these are lower and shorter (see Figure 2) and resulted in a sinuous (salient) planform allowing flow around the structures during all phases of the tide (FLEMING and HAMER 2000).

The Sea Palling site differs from those at many other segmented breakwater systems due to an interaction between the asymmetric, shore-parallel tidal currents and the semi-emergent tombolos behind the Phase 1 breakwaters. During the high-water flood phase of the tide, strong tidal currents transport sediment from the submerged tombolo surfaces, driving a pulse of sand towards the south-east. During the opposite low-water ebb phase, the emergent tombolos are dry and the sediment flux is not balanced by a return towards the north-west.

Southern North Sea Tides

The close proximity of two amphidromic points in the shallow southern-bight of the North Sea, create the non-linear effects which influence and create the locally, complex tidal regime (HR WALLINGFORD, 2002). The resultant, "progressive-wave" system has a typical Spring range of 3.0m, a Neap of 1.3m and asymmetry

Figure 1. Location of Sea Palling on the north-east coast of Norfolk, UK.

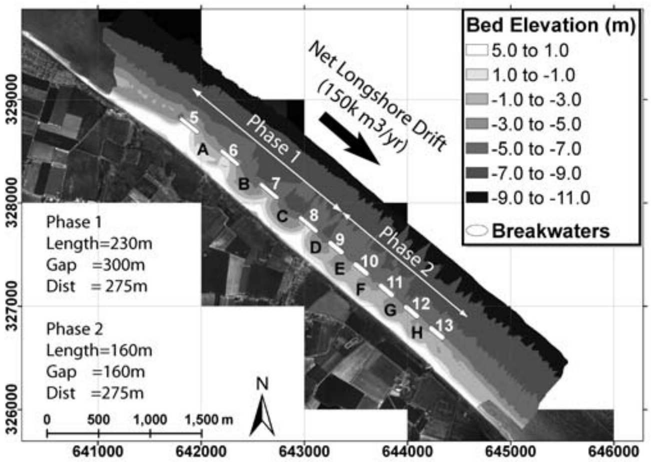

Figure 2. Configuration of the nine Sea Palling breakwaters, design parameters and immediate bathymetry (April, 2006).

between both amplitude and wavelength of the flood/ebb cycle. A strong diurnal inequality exists and shore-parallel currents of up to $1ms^{-1}$ flow around the breakwaters. Offshore, tidal velocity peaks at $\sim 1.6ms^{-1}$.

Wave Climate and Storm Response

Assessment of the local wave climate is crucial in determining the rates and direction of sediment transport along the drift-aligned cell between Happisburgh and Winterton (VINCENT, 1982). Waves reach the shore at Sea Palling in a range of directions between northwest and southeast. The largest waves are from the north and northeast. Significant wave heights H_s of 7.6 m, 9.7 m and 11.1 m with return periods of 1, 10 and 50 years respectively, have been estimated for offshore Sea Palling (HALCROW, 1991). The importance of the "Norfolk Banks", shore-parallel sand banks off-shore from Sea Palling, in attenuating off-shore waves, was noted by DELFT (1995). The breakwaters were designed to give protection against storm waves elevated by a 4m-surge, as occurred so catastrophically throughout the North Sea basin in 1953. The beaches in the region display considerable short-term volatility during storms; analysis of beach profile data show that cross-shore sand movements of up to 1,000,000 m^3 can occur along the 14km regional cell during storm events. An analysis of wave events during the winter of 2003/2004, the most comprehensive study of the response of the breakwaters to individual storms (DOLPHIN et al., 2004), noted that whilst waves are responsible for the greatest morphological changes, tidal currents, tidal range and the local morphology determine sediment pathways through the breakwaters. HALL and DAMGAARD (2000) noted that the critical wave height for the initiation of wave-generated sediment transport at Sea Palling was H_s = 0.5m. Wave climate studies indicate that conditions typical of this low-energy wave environment occur for around 70% of the time at Sea Palling, a period when tidal currents may dominate sediment mobility.

Longshore Sand Transport

VINCENT (1979) calculated that the typical annual sand transport past Sea Palling was 148k m^3, in a southeastward direction although significant variability in this value is evident year on year. During the design of the breakwaters, numerical models suggested much higher sand fluxes and showed wide diversity in longshore transport rates, between 970,000 m^3 to the southeast and 384,000 m^3 to the northwest in consecutive years. Most models ignored tidal currents, although some assessed the impact of varying tidal water level. DELFT (1995) noted the capacity of the long-shore bar as a conduit for longshore sediment transport although construction of the breakwaters on the bar now interrupts this mechanism. THOMALLA and VINCENT (2003) observed substantial reduction of inter-seasonal cross-shore transport after construction of the breakwaters; sand trapped in the breakwater system formed salients and tombolos in the sheltered waters behind the breakwaters and that destruction of the long-shore bar between the breakwaters allowed higher waves to penetrate into the embayments, further lowering beach levels.

Objectives and Methodology

The major interruption of the longshore sediment transport by the breakwaters is evident by the build-up of sand in the tombolos, salients and the quasi-permanent, sub-aerial deposits on the back-beach (above MHWS). In contrast to early studies of this breakwater system which focussed on waves and ignored tides, this paper examines the interactions between the tidal currents, the breakwaters and the local morphology and to examine how the tides may influence and ultimately control wave-generated transport through the breakwater system. The study used a numerical model to compute shear stresses and sand fluxes generated by a) tidal currents alone, and b) with stirring by small waves in the lee of the breakwaters. These "background" low-energy, conditions correspond with periods when tidal currents dominate. To validate the model high-resolution RTK-GPS beach surveys were made to determine the topographic changes each day and together with field measurements of waves, tidal components, bedform evolution and suspended sand concentrations to determine sand fluxes over the tombolos.

An assessment of how the sediment budget and sand pathways through the breakwaters have changed since their installation is made and an appraisal of how these aspects may develop in the future.

NUMERICAL MODELLING

The modular, engineering-level model TELEMAC, published by EDF-LNH, was used to model the tidal currents and the wave effects. The depth-averaged (2DH) currents model TELEMAC2D, solves the Saint-Venant equations over an irregular, finite element

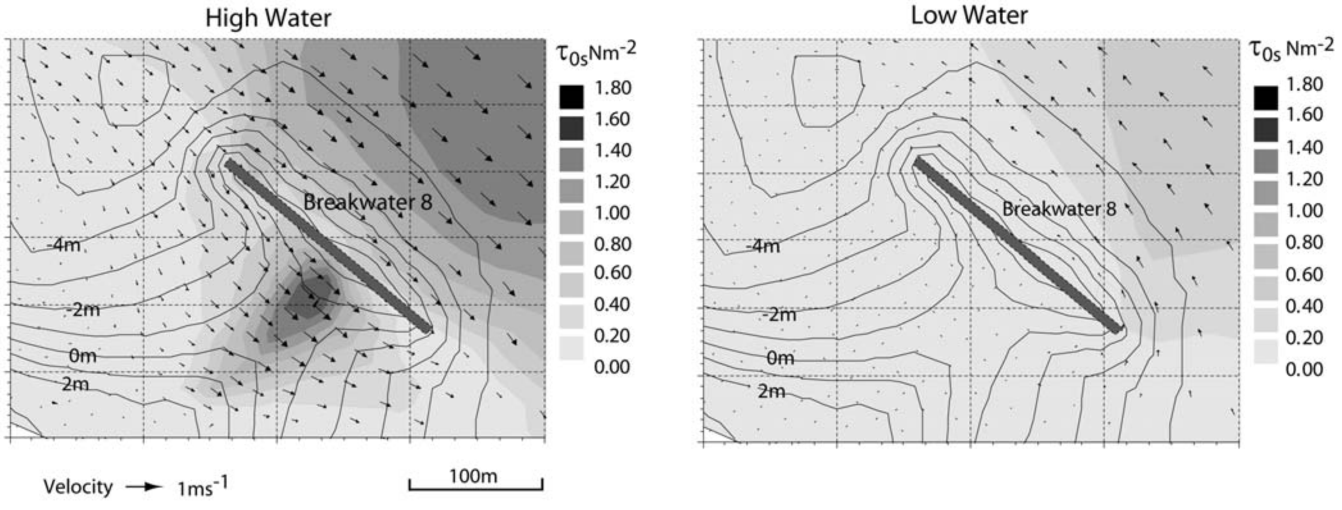

Figure 2. Skin-friction bed shear stress and current vectors over the tidal-tombolo inshore of breakwater 8, at MHWS and MLWS, showing the effective blocking of northwestward sand fluxes during the low tide. Critical value for τ_0s is 0.227Nm^{-2}.

mesh. The model domain covered the first four Phase 1 breakwaters to a distance of 2km off-shore.

For modelling shallow water wave transformation, three modules are available to the TELEMAC user. Two modules (TOMAWAC and COWADIS) solve the wave directional spectrum equation including the effects of refraction and breaking but not reflection or diffraction. The effect of diffraction is important when modelling wave propagation around breakwaters, not only for assessing morphological evolution of the shoreline and tombolo planform but to ensure wave energy reaches the lee of the structure (ZYSERMAN and JOHNSON, 2002).

The ARTEMIS wave module includes diffraction around and reflection from breakwater structures and so was used here; it solves the elliptic, mild-slope equation modified to include energy loss due to bottom friction and breaking. ARTEMIS requires a minimum of four mesh nodes per wavelength to delineate the wave surface sufficiently, an unreasonably large number for most tidal domains so ARTEMIS is often formulated in micro-scale to accept boundary conditions from either of the other two wave modules.

As the version of TELEMAC used here (5.1) is not fully interactive in its treatment of waves and currents, we combined the TELEMAC2D outputs of tidal currents and water depths with the wave field from ARTEMIS and use the Soulsby - Van Rijn formulation to compute the total-load transport rate (SOULSBY, 1997). The method is particularly appropriate where the bed is rippled. An orthogonal grid over the tombolo was nested into the finite-element mesh and values for sand transport and subsequent bed evolution computed using a continuity equation approach.

Currents

To replicate the progressive tidal wave at Sea Palling into the TELEMAC2D simulation, tidal currents were prescribed at one of the two shore-normal boundaries of model domain and tidal levels prescribed at the other end. Boundary conditions were obtained from field measurements made by HR WALLINGFORD, as part of the performance monitoring for the breakwaters; data from a shore-normal ADCP transect were used to define the cross-shore velocity profile for the velocity boundary.

A 17-day tidal simulation (Spring-Neap-Spring) showed that currents produce sufficient bed-shear stress to erode material from the tombolo surfaces on six tides either side of the peak Spring cycle. Boundary conditions were chosen to represent the “background”, low-energy condition ($H_s \approx 0.5$m). Figure 2 shows the distribution of skin-friction bed shear stress with coincident current vectors around a Phase 1 breakwater and its tidal-tombolo, during high and low water of a peak Spring tide, correspond to times of peak flood and ebb flows respectively. This shows the blocking to northwestward transport by the emergent tombolo. During the flood, shear stress peaks strongly over the tombolo; a flow acceleration of ~30% occurs with the reduction in flow layer thickness immediately over the tombolo. During the ebb, bed shear stresses remain sub-critical everywhere inshore of the breakwaters and for ~50m seaward and flows in the embayments on either side of the tombolo are effectively suppressed.

Tidal and Sediment Transport Asymmetry

Several factors contribute to the asymmetry of sediment transported by tidal currents and are demonstrated by the TELEMAC model results:

1. The observed pulse of southeastward sand transported reaches a maximum value during Spring tides.
2. The southeastward flood tide (high-water) is of slightly shorter duration but stronger current speed than the northwestward ebb tide (low-water), resulting in a residual flow towards the southeast (H.R.WALLINGFORD, 2002). The residual drift is towards the southeast with water travelling 24% further to the southeast on the flood tide than to the northwest on the ebb. This residual also varies with the Spring - Neap cycle and is a maximum at times of Spring tides.
3. The tides exhibit a diurnal inequality which reaches a maximum during the Spring tides. Water level variations of up to 0.7m occurring between consecutive high tides and low tides act to exacerbate asymmetry in the direction of sand transport. At deep water the inequality always results in a strong southeastward pulse. At shallow water the low level drives either a very short northwestward flow or no flow at all.
4. Cross-shore flow, from or to the off-shore domain is also tidally controlled. When flow is blocked by the tombolos at low water, flow into/out of the embayment is much reduced or ceases altogether and the northwestward flowing tidal currents bypass the breakwaters. During the flood, a small component of cross-shore sediment transport is predicted.

Volumetric transport rates were determined from tidal currents only, using NIELSEN (1992) for bedload and VAN RIJN (1984b) for suspended load. Volumetric sand transport values are shown in Table 1; these are the peak value (at high water) on the apex of the tombolo during four tides over the highest Spring tides, over the lowest four Neap tides and during four ‘average’ tides during the transition between Spring and Neap.

Effect of Waves

The effect of the non-linear, wave-current interaction and the enhancement to sand transport from stirring was determined using the ARTEMIS module at mid-flood, high, mid-ebb and low water levels of a peak Spring, a Neap and with increasing and decreasing mid-tidal range tides. Mono-directional, random waves with H_s=0.5m; T_p= 5s and varying obliquity were used. Although beach face sand at Sea Palling is medium to coarse (d_{50}=430µm), stirring by small waves enhances overall transport rates by a factor of ~ 3.5 and increased suspended sand transport by an order of magnitude over the values predicted for currents only.

Only minor transport towards the northwest is predicted; around Neap tides bed-shear stresses fall below the critical value even though a northwestward flow exists (due to higher low-water levels and reduced diurnal inequality) and no transport occurs; during the Spring tides the tombolo emerges, blocking flow and transport over most of the northwestward phase of the tidal cycle. In the embayments between breakwaters, shear stress drops below the level critical for bedload transport, as can be seen in Figure 2, although the Soulsby - Van Rijn model predicts a small suspended component over the embayment region from 0.5m high waves. The volume of material leaving the breakwater system via cross-shore motion was evaluated using field measurements of cross-shore flow.

The dominance of southeastward transport will result in the migration of the tombolo axis to the southeast and transport of sand into the adjacent, southerly embayments although the model used here does not include a bed-update in the hydrodynamic computation.

Table 1: Predicted Peak Volumetric Sand Transport Rate – Comparison of cross-tombolo sand transport between a) tidal currents only and b) currents plus wave-stirring. Subscripts b and s denote bedload and suspended load. All rates are towards the south-east

Tide	Currents only ($\times10^{-5}$ m^2s^{-1})		Currents + Waves ($\times10^{-5}m^2s^{-1}$)	
	q_b	q_s	Q_b	Q_s
MHWS	1.84	0.61	1.76	6.16
MHW	0.38	0.03	0.39	1.32
MHWN	-	-	-	-
MHW	0.60	0.18	0.33	1.11

FIELD VALIDATION

A short field campaign was carried out around a tombolo inshore of one of the Phase 1 breakwaters to measure sand fluxes directly over the tombolo and provide validation data for the model. An acoustic backscatter system measuring suspended sand transport, an upward-looking AquaDopp current profiler monitoring the currents, and 2D acoustic bed-form imaging system were deployed on the apex of the tombolo with additional current profilers in the adjacent embayment and the breakwater gap. Bedload transport rates were deduced using the bed-form migration celerity, adopting the method shown in SOULSBY (1997). Current velocity and suspended sediment concentration profiles were integrated to give suspended sediment fluxes. The derived transport values related to the wave-stirred transport and show good agreement (within 50%) with predicted results although the time series of measured and predicted results were not fully coincident.

RTK-GPS surveys of the tombolo and embayment beach-face made each day, show good agreement with the predicted tombolo evolution using the SOULSBY-VAN RIJN transport equation. An ADCP transect across the breakwater gap during a flood/ebb cycle provided a cross-shore flow depth profile and enabled quantification of sediment losses across the breakwater lines to the off-shore domain, based upon modelled values for suspended sediment concentration in the embayments.

DISCUSSION

Effects on Longshore Transport

Extrapolating the predicted sand transport rates to annual values, ~40,000 m^3 is transported through the breakwater system by tidal currents plus stirring by small waves (BACON, 2005). Some sand is exported off-shore into the regional domain, or into Phase 2 of the system. Whilst of modest magnitude compared to the pre-breakwater longshore transport estimates e.g. ~150,000 (VINCENT, 1979) this represents the background value to which storm wave or surge conditions will add.

The tombolos developed rapidly almost immediately the Phase 1 breakwaters were in place (THOMALLA and VINCENT, 2004) and have been a permanent feature of the Phase 1 breakwaters; they are indicative of the barrier that the breakwater system imposes on the local longshore transport of sand. The most northerly (updrift) tombolo is almost permanently emerged and allows only a minor southeastward flow at the highest Spring tides; beaches immediately (~500m) to the north of the breakwater system are building. The most northerly embayment (A – see Figure 2) is now very shallow and at low Spring tide is almost dry. Embayment B is now becoming more shallow.

Implication for Local Sediment Pathways

Whilst the Sea Palling breakwaters are considered a success in providing an adequate storm defence (FLEMING and HAMER, 2000), the perturbation of the regional sediment transport is considerable and was difficult to predict or quantify. The importance of the tidal regime in maintaining some sediment transport southeastward through the breakwaters system is clearly demonstrated with these results. The morphological control on the longshore sediment flux has important consequences for the beaches down-drift of Sea Palling where substantial quantities of re-nourishment have been necessary to maintain beach levels during the ten years since the breakwaters’ completion. Quantities of up to 500,000m^3 of beach re-nourishment from dredged sources off-shore have been placed on the downdrift beaches and in the breakwater region every two or three years since 1997. Rock revetments in the Phase 2 area have been crucial to defending the sea wall from embayment erosion.

Varying tidal levels have also been shown to control the degree of storm-generated, diabathic sediment exchange with removal of material from the beach-face into the embayments (DOLPHIN et al, 2004). Tidal level also influences the degree to which the flanks of tombolos are eroded during the most intense storms which are from the north.

The infilling of the two more northerly embayments is indicative of (some) sand entering the breakwater system from the updrift beaches; however the combination of tidal currents and small waves described here cannot be the mechanism – it is likely to occur during northerly storm events which are often accompanied by surges which increase mean sea levels by 1-2 m (the most northerly tombolo is then overtopped). Once into the system sand can be transported southeastwards by both tidal currents and storm waves. The lowering of the down-drift beaches shows that sufficient sand is not getting through the system. It is accumulating updrift of the breakwaters, within the breakwater system, on the backbeaches and, more speculatively, in the region off-shore of the breakwaters either through offshore transport through the breakwater gaps or directly bypassing offshore of the breakwaters.

Evolution over a Decade

After installation of the Sea Palling system, beach morphology in-shore of the breakwaters evolved rapidly and drastically. Since then, beach topography has changed more subtly and new sediment pathways have developed after the initial interruption to longshore flux. The LEACOAST2 (2005-8) project is now measuring, monitoring and modelling these changes in detail to determine how the breakwaters impact upon the regional sediment budget. Beach topography and bathymetry surveys carried out monthly since August, 2005 show some accumulation of sediment seaward of the breakwaters. A significant build-up of sand is observed at each end of the system, to the seaward of the end breakwaters and in the immediate down-drift regions. Previous monitoring using beach profiles has not provided sufficient resolution to detect these changes. Bathymetry within Phase 2 breakwaters shows a similar build-up although erosion in embayment E (Figure 2) continues to be a problem. The process experiments currently underway will provide measurements of sufficient resolution to develop the likely sediment pathways into and through the Phase 2 breakwaters.

CONCLUSION

The interaction of the complex local tidal regime in the Southern North Sea with the breakwaters, beaches and tombolo morphology exerts significant control on how sediment passes over the tidal-tombolos behind the Sea Palling breakwaters. The tide generates a small component of sand transport during low wave energy conditions equivalent to ~20% of the pre-construction longshore sand transport and coincident with its direction. Further evolution of the system is likely as embayment filling continues such that even ten years after their construction, a morphological equilibrium has not been reached and the system continues to evolve.

LITERATURE CITED

BACON, J.C., 2005, The Shore-Parallel Breakwaters at Sea Palling: Interaction with Tidal Currents and Contribution to Sand Transport. Norwich, U.K.; University of East Anglia, Ph.D. thesis, 229p.

DELFT, 1995. Review – Happisburgh to Winterton Sea Defences. Delft, Netherlands. Delft Hydraulics.

DOLPHIN, T.J.; TAYLOR, J.; VINCENT, C.E.; BACON, J.C.; PAN S.; O'CONNOR, B.; 2004. Storm scale effects on shore-parallel breakwaters at Sea Palling. *Proceedings of the 26th International Conference on Coastal Engineering Vol 3,* (Lisbon, Portugal, ASCE) pp 2849-2861.

FLEMING, C. and HAMER, B., 2000. *Proceedings of the 24th International Conference on Coastal Engineering,* (Lisbon, Australia, ASCE) pp 1813-1820.

HALCROW, 1991. Final Report on Proposed Sea Defences – Vol 2, Appendices, Swindon, U.K.: Sir William Halcrow and Partners Ltd.

HALL, L. and DAMGAARD, J. (2000). Simulation of sediment transport and morphological development at the Happisburgh to Winterton Reefs. *Technical Report TR108*, HR Wallingford (UK).31p

HR WALLINGFORD, 2002. Southern North Sea Sediment Transport Study. Wallingford, U.K.: HR Wallingford Ltd., CEFAS/UEA, Posford Duvivier, D'Odolier, B., *Technical Report EX4526*, Phase 2 – Final Report, on CD.

KING, D.M.; COOPER, N.J.; MORFETT, J.C.; POPE, D.J., 2000. Application of offshore breakwaters to the UK: A case study at Elmer beach. *Journal of Coastal Research* 16(), 172-187.

LAMBERTI, A.; ARCHETTI, R.; KRAMER, M.; PAPHITIS, D.; MOSSO, C.; DI RISIO, M., 2005. European Experience of Low Crested Structures for Coastal Management. *Coastal Engineering,* 52, 841-866.

NIELSEN, P., 1992. Coastal Bottom Boundary Layers and Sediment Transport, Singapore. World Scientific Publishing. 324p

SOULSBY, R., 1997. Dynamics of Marine Sands, London, U.K: Thos. Telford. 225p.

THOMALLA, F., and VINCENT, C., 2003. Beach response to shore parallel breakwaters at Sea Palling, *Estuarine and Coastal Shelf Science.,* **56,** 203-212.

THOMALLA, F. and VINCENT, C., 2004. Designing Offshore Breakwaters Using Empirical Relationships: A Case Study from Norfolk, United Kingdom. *Journal of Coastal Research*, 20(4), 1224-1230.

VAN RIJN, L., 1984B. Sediment Transport, Part II: Suspended load transport, *Journal of Hydraulic Engineering* **110** (12) 1733-1754.

VINCENT, C.E., 1979. Longshore sand transport rates – a simple model for the East Anglian coastline. *Coastal Engineering,* 3(), 113-136.

VINCENT, C., 1982. Wave climate and longshore wave power. *East Anglian Coastal Research Project – Technical Report 7.* University of East Anglia, Norwich, U.K. ##p.

ZYSERMAN, JULIO A. and JOHNSON, HAKEEM K., 2002. Modelling morphological change in the vicinity of shore-parallel breakwaters. *Coastal Engineering* 45, 261-284.

ACKNOWLEDGEMENTS

The study was carried out as part of a PhD studentship from the University of East Anglia, part funded by a case award from EPSRC and the LEACOAST project, grant GR/R83552/01.The authors would like to thank the Environment Agency and HR Wallingford for supplying data for boundary conditions and the TELEMAC modelling suite.