Tidal effects on cross-shore sediment transport on a shingle beach

Authors: Trim, L. K., She, K., and Pope, D. J.

Source: Journal of Coastal Research, 36(sp1) : 708-715

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/1551-5036-36.sp1.708

Journal of Coastal Research | SI 36 | 708-715 | (ICS 2002 Proceedings) | Northern Ireland | ISSN 0749-0208

Tidal effects on cross-shore sediment transport on a shingle beach

L. K. Trim, K. She and D. J.Pope

School of the Environment
University of Brighton
Lewes Road, Brighton,
East Sussex, BN2 4GJ, UK
k.m.she@bton.ac.uk

ABSTRACT

This paper presents a model study of the sediment transport processes of a shingle beach under the combined action of waves and tides. Parallel experiments were carried out with a constant water depth corresponding to the high water level of the tidal experiments, thus allowing a direct comparison between the two cases. It was found that the presence of the tide affected the beach behaviour differently depending on the wave climate. Under storm conditions, a rolling bar was clearly seen moving below the Mean Water Level (MWL) with both the flood and ebb tides. Under swell conditions on the flood, sediment was eroded once a critical depth had been reached but was moved onshore in the uprush to form the berm. The presence of the tide was shown to increase the size of the berm in a summer profile, and push the offshore bar further seaward in the winter profiles. The overall beach slope did not change when subjected to the wave attack without the tide but altered significantly under the combined action of the wave and the tide.

ADDITIONALINDEXWORDS: *sediment transport, tidal effects, beach modelling, beach profiles*

INTRODUCTION

Laboratory beach models have been extensively used to investigate sediment transport processes under the action of waves. However, the effects of the tide have rarely been taken into account when setting up these models. In reality, beach evolution is due to the combined effect of waves and the tide. In a recent study by the authors (SHE *et al*., 2000), a shingle beach was monitored over a twenty-four hour period with the beach profiles and wave conditions recorded. The beach was then modelled at a 1:12.5 model scale at constant mean still water depth. The model successfully reproduced the profile changes for the upper section of the beach but significant discrepancy existed in the lower section. It was suggested that such differences were largely due to the absence of the tide in the model.

While it is extremely difficult to perform measurements of dynamic beach profiles under field conditions, it is relatively easy to introduce tides into a beach model and to continuously monitor the profile changes of the beach. This paper presents the results of a laboratory model study of the sediment transport processes of a shingle beach under the combined action of waves and tides.

EXPERIMENTAL PROCEDURE

The model beaches were constructed in a 10m x 0.45m x 0.5m flume at the University of Brighton. The model beach material was made of sands with D_{10} = 0.11mm, D_{50} = 1.1mm, D_{100} = 4.0mm and D_{84}/D_{16} = 9.41. The model was intended to represent a prototype beach of bimodal mixed sand and shingle at a model scale of 1:12.5. The corresponding prototype sediment characteristics are D_{10} = 0.26mm, D_{50} = 13.4mm, D_{100} = 50.0mm. Detailed discussions on the sediment scaling laws can be found in SHE *et al*. (2000). The high water depth of the model was 0.28m and the depth variation followed a simplified tidal model as indicated in Figure 1.

Two beach slopes (1/7 and 1/9) were examined, each subjected to two wave conditions of the same period but different wave heights (Table 1). Waves were generated by a PC operated DC piston-type wave generator. For each given significant wave height and period, a random wave field was created in terms of Jonswap Spectrum. The corresponding prototype (natural) wave conditions are Hs = 1m and Ts = 6secs for Condition I, and Hs = 1.875m and Ts = 6secs for Condition II. In parallel with the tidal experiments, bench marking experiments were carried out for each beach slope and wave condition but with a constant water depth of 0.28m (Table 1).

Table 1. Experimental details

	Beach Gradient (1/7)	**Beach Gradient (1/9)**
Condition I (Hs=80mm, Ts = 1.7secs)	**Experiment 7A:** Water depth = constant (0.28m)	**Experiment 9A:** Water depth = constant (0.28m)
	Experiment 7B: Water depth = tidal (HW = 0.28m)	**Experiment 9B:** Water depth = tidal (HW = 0.28m)
Condition II (Hs = 150mm, Ts = 1.7secs)	**Experiment 7C:** Water depth = constant (0.28m)	**Experiment 9C:** Water depth = constant (0.28m)
	Experiment 7D: Water depth = tidal (HW = 0.28m)	**Experiment 9D:** Water depth = tidal (HW = 0.28m)

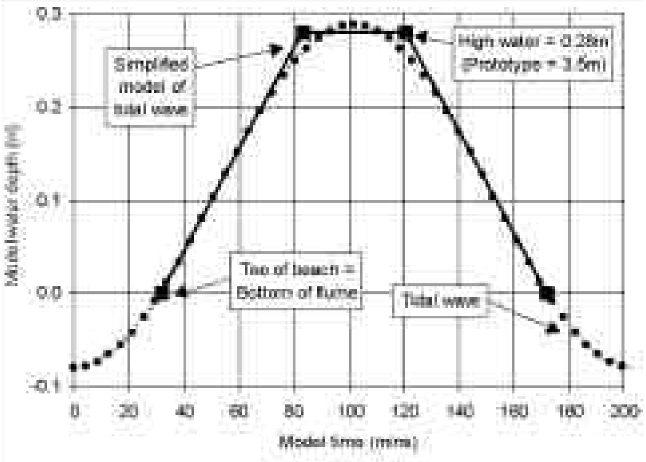

Figure 1. Simplified tidal cycle.

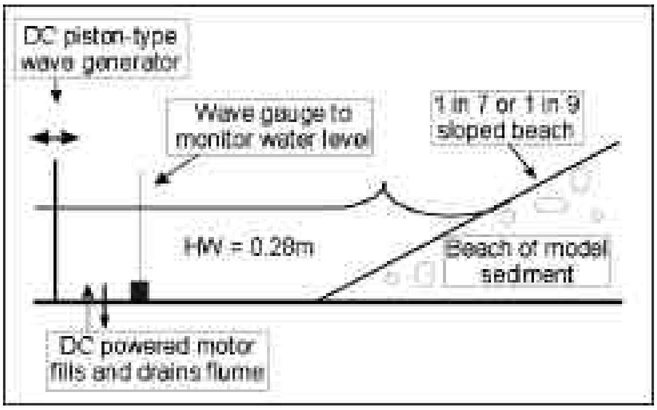

Figure 2. Sketch of experimental set-up.

Prior to each experiment the beach was moulded so that the correct beach slope was represented. The test duration of each constant water depth experiment was 57 minutes, representing the peak period of the tidal cycle. This equates to a prototype time of 3hrs 20mins. The tidal experiments each took 140 minutes. Once the wave machine had started, water was slowly pumped into the flume using a DC motor powered pump. The flume was filled and drained to simulate the simplified tidal cycle given in Figure 1. The actual mean water level was continuously monitored throughout each experiment using a 350 mm wave gauge. The rate of filling or draining was adjusted against the theoretical curve given in Figure 1. It should be noted that the current experimental setup is a simplified presentation of the tidal phenomenon in the ocean. The setup does not *yet al*low the inclusion of the tide-induced currents in the model.

Each experiment was video recorded and each profile recorded manually every ten minutes. The experimental set-up is shown in Figure 2.

RESULTS AND DISCUSSION

The inclusion of a tidal component has shown significant effects on the beach profile development. When a constant water depth was used, sediment movement and thus profile change was restricted to the area surrounding the MWL. Under a tide the whole beach face became involved in the cross-shore sediment mechanics.

A brief summary of the benchmark experiments is given here before proceeding to the detailed description of the tidal experiments. Figure 3 shows the typical time dependent behaviour of the beach when subjected to a random wave field with a constant water depth. The most significant profile changes took place in the first few minutes of the test run after which the beach profile reached a pseudo-steady state. The resulting beach profile after each test run depended on both the initial beach slope and the wave condition, as can be seen from Figure 4. With Hs = 80mm and Ts = 1.7s, onshore transport was observed for both the 1/7 and 1/9 slopes, resulting in a typical swell profile on the beach. As the wave height was increased to Hs = 150mm, the direction of sediment movement remained in the onshore direction for the 1/9 slope but offshore transport was observed in the 1/7 slope experiment, leading to a typical storm profile on the beach.

Swell profiles are normally associated with onshore transport under the action of swell waves. Current experiments clearly show that swell profiles can also be a result of random wave action. The direction of sediment movement, and thus the final form of the beach profile depends on both the beach slope and the incident wave energy.

Swell profiles

Figures 5 and 6 present the beach profiles recorded during the tidal cycle on the 1/9 beach under Conditions I and II. It may be seen that profile changes under a tidal influence become much more complex.

On the flood tide, sediment is eroded around the MWL once a critical depth was reached and was pushed up the beach by the uprush. For all profiles and wave conditions, this ‘critical’water depth was found to be around 0.2 metres model water depth, equivalent to ~70% of the high water depth. The ‘critical’water depth was defined as the point at which a great surge in sediment activity occurred. As the tide level increased, the eroded area under the MWL increased both in width and depth creating a plunging trough. This feature may also be named a ‘step’. A ‘step’ being a characteristic feature of reflective beaches (Wright and Short, 1983). As the beaches in our experiments were not classified in such terms, the name ‘plunging trough’will be used. At high water the continued sediment erosion deepened and widened the trough. Eroded sediment was pushed shorewards in the uprush and formed a small berm on the upper shore. During the ebb tide the accreted sediment at the top of the beach remained stranded. As the MWL decreased, the point of wave breaking gradually moved in the seaward direction, thus moving beach material shorewards from further down the beach. As a result the plunging trough became shallower as it was filled with sediment transported from further offshore. At the end of the tidal cycle, no obvious plunging trough was seen on the beach profile.

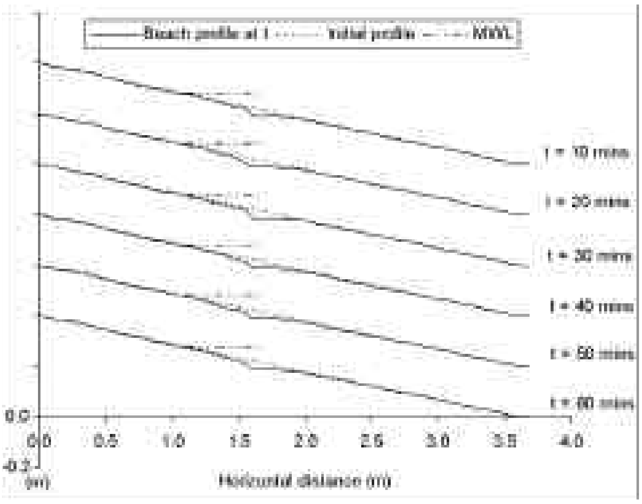

Figure 3. Time dependent beach profiles recorded from the constant water depth experiment on a 1 in 9 beach under Condition I.

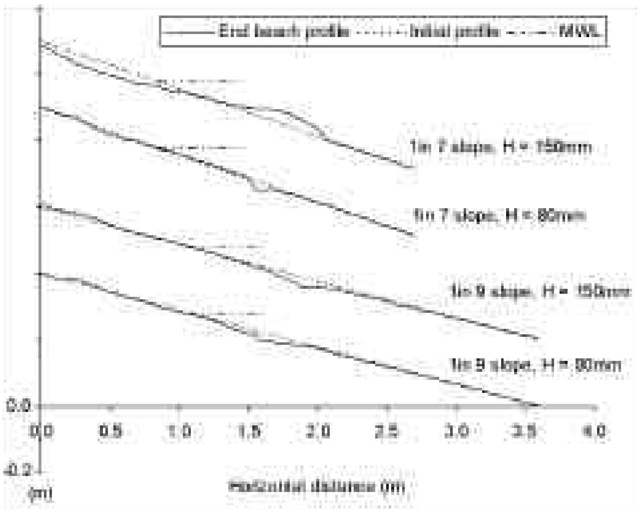

Figure 3. Time dependent beach profiles recorded from the constant water depth experiment on a 1 in 9 beach under Condition I.

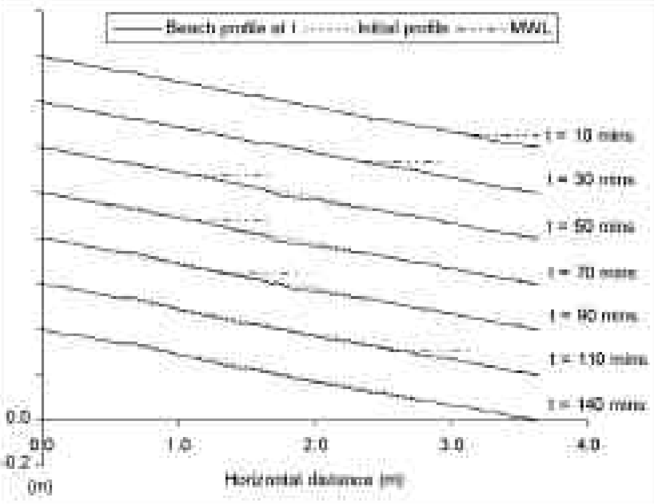

Figure 5. Time dependent beach profiles recorded from the tidal water depth experiment on a 1 in 9 beach under Condition I.

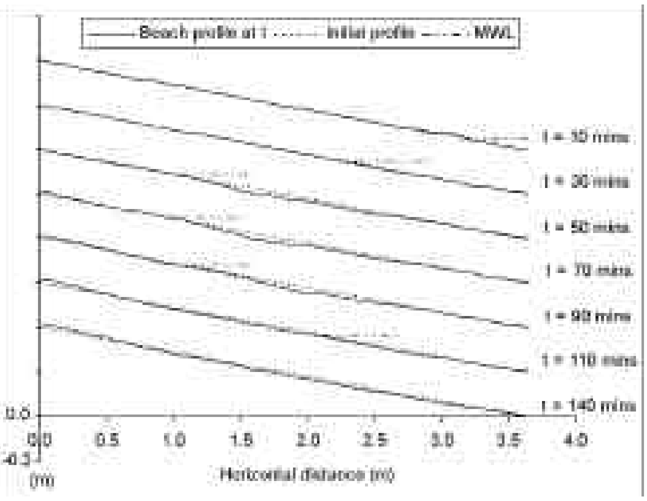

Figure 6. Time dependent beach profiles recorded from the tidal water depth experiment on a 1 in 9 beach under Condition II.

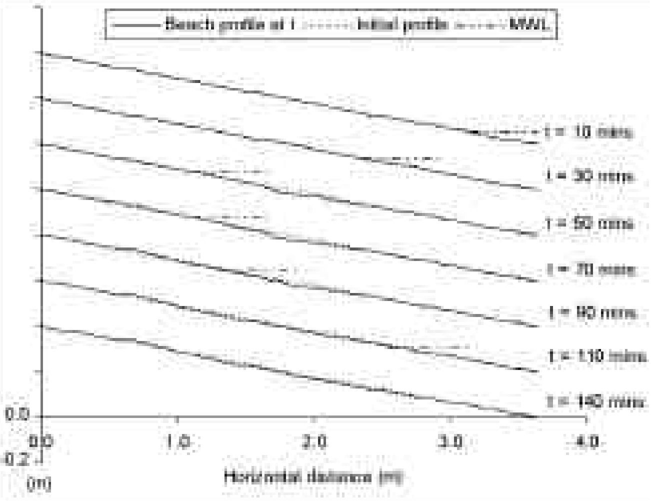

Figure 7. Net profile changes in high water and end profiles recorded on the 1 in 9 beach under Condition I.

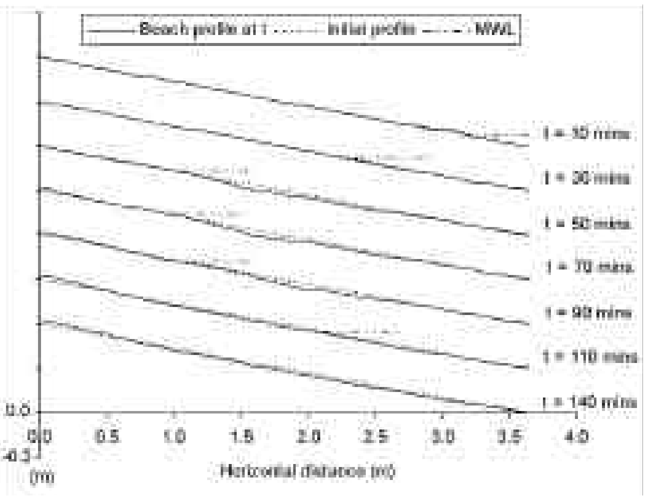

Figure 8. Net profile changes in high water and end profiles recorded on the 1 in 9 beach under Condition II.

For the 1/9 slope experiments, two significant differences were noted between the resulting profiles when the constant water depth and tidal water depth profiles were compared:

1) In the constant water depth experiment, a clear plunging trough formed on the beach profile within a short time of starting a test. In the tidal experiment, no clear plunging troughs were observed during the flood or ebb tide but the trough became obvious shortly after high water was reached. This means that a plunging trough in the beach profile can only occur when the water level remains constant for a sufficient period of time. Figures 7 and 8 show the associated net profile changes at the end of the high water, at the end of the tidal cycle, and at the end of the constant water depth experiment. The high water profiles of the tidal experiments closely resemble the constant water depth end profiles. It may be noted that the end profile of a tidal cycle significantly differs from that at the end of high water or that at the end of the constant water depth test.

2) In the tidal experiments, sediment was moved gradually onshore during the flood tide. Sediment gathered from the lower slope accreted on the upper shore. When a constant water depth was used, erosion could only occur across a small section of the beach and thus the sediment available for accretion on the upper shore was reduced. The resulting berm in the constant water depth experiments was therefore smaller.

Storm profiles

When the 1/7 slope beach was tested under wave Condition II, erosive profiles, typified by a large area of erosion on the upper shore and an offshore bar, were recorded (Figure 9). During the flood, sediment was eroded from the beach face by the progressing uprush and accumulated into a rolling bar below the MWL. The bar moved shoreward with the rising water level. At high water, sediment continued to be eroded from the upper shore and was added to the growing offshore bar. On the ebb, the offshore bar was moved further offshore whilst gradually diminishing in size as its sediment was redistributed along the lower shore.

Figure 10 shows the net profile changes at the end of high water and at end of the tidal cycle in comparison with the end profile of the constant water depth test. The high water profile of the tidal experiment shows excellent agreement with the end profile of the constant water depth experiment. When comparing the tidal experiment end profile and the constant water depth profile, it can be seen that under the influence of the ebb tide the accreted sediment is moved offshore, effectively spreading out across the lower half of the beach. The characteristic bar is removed by the receding tide. The complete movement of sediment offshore can not be achieved unless a tidal component is present.

Intermediate profiles

Figure 11 shows a unique behaviour observed with a 1/7 beach slope under Condition I. Up to the end of high water level, the sediment was moved onshore resulting in accretion at the top of the beach and the formation of a plunging trough below MWL. The beach profile at the end of high water was similar to that obtained from the constant water experiment, as indicated by Figure 12. During the ebb tide, the beach material was moved from the upper section of the beach to the lower section. This means that both onshore and offshore transport takes place within one tidal cycle. Although the top section of the beach had gained material, the material movement to the lower sections of the beach was significantly more. As a result, the end tidal profile clearly represented a storm profile. In the absence of a tidal component, the general motion of this beach may have been misinterpreted.

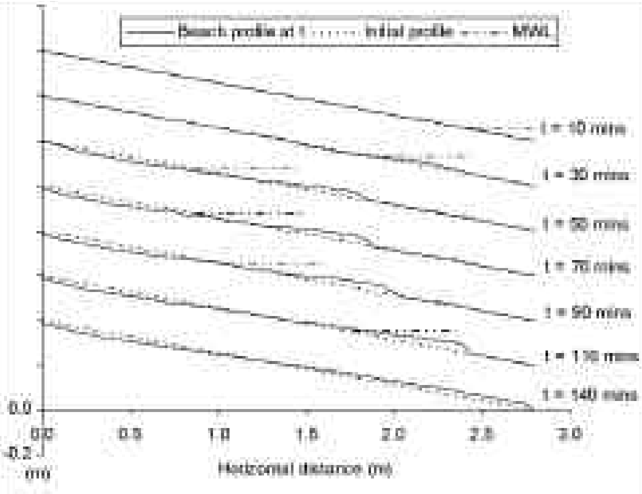

Figure 9. Time dependent beach profiles recorded from the tidal water depth experiment on a 1 in 7 beach under Condition II.

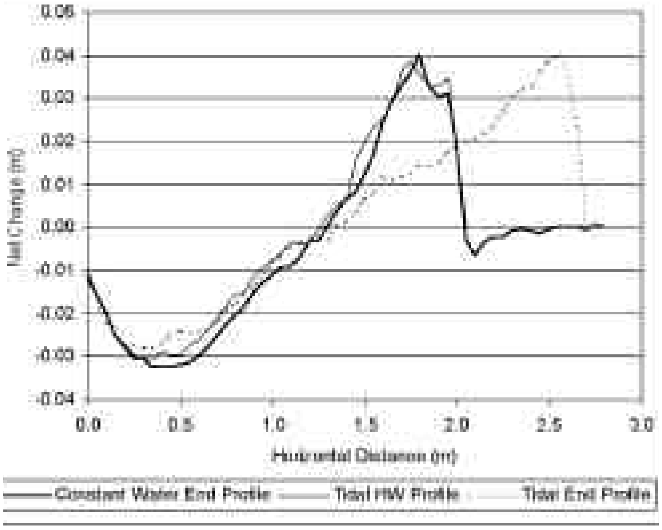

Figure 10. Net profile changes in high water and end profiles recorded on the 1 in 7 beach under Condition II.

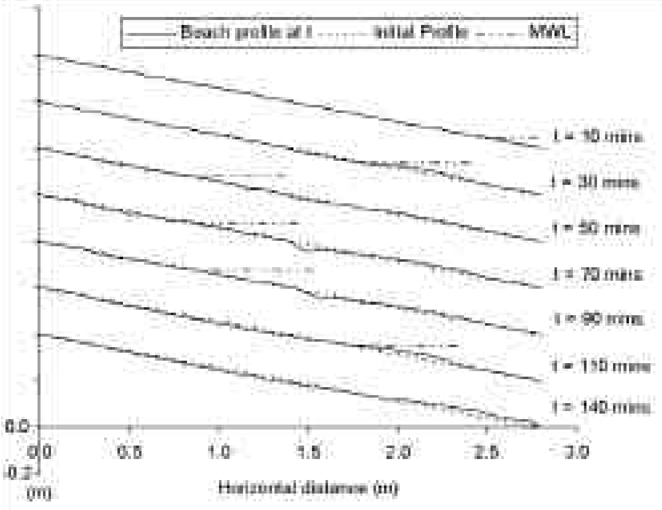

Figure 11. Time dependent beach profiles recorded from the tidal water depth experiment on a 1 in 7 beach under Condition I.

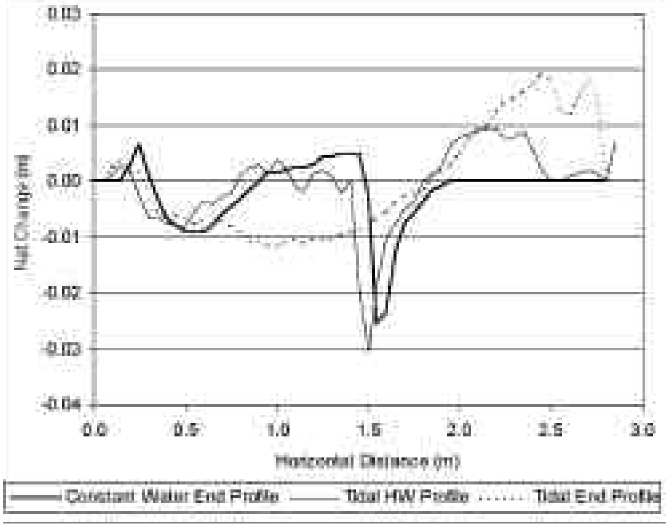

Figure 12. Net profile changes in high water and end profiles recorded on the 1 in 7 beach under Condition I.

Influence of wave height

When the swell profiles produced under Conditions I and II on the 1/9 slope are compared, it may be seen that the influence of the increased wave height is most obviously seen in the upper portion of the profile. The width of the surf zone was seen to increase in response to the increased wave height and wave energy, with the larger berm being located at a greater distance above the MWL under Condition II. This agrees with HUGHES and CHIU'S (1981 cited in POWELL, 1990) supposition that the extra surf zone volume necessary to dissipate an increased incident wave energy is obtained by a lengthening of the surf zone rather than by a change in profile. The increased wave energy level resulted in greater net transport, which was exhibited in the larger berm size and wider trough of the Condition II profile. The location of offshore accretion occurred further seaward under the larger wave height.

The main impact of the greater wave height on the 1/7 beach is that a storm profile rather than an intermediary profile was produced. The increased wave steepness caused by the larger wave height favours the movement of sediment offshore. This confirms the findings of other authors who have determined that wave steepness is a critical parameter in defining beach sediment movement direction and resultant beach profile (DEAN, 1973).

Effects of initial beach slope on resultant profile

A reduction in beach slope causes wave breaking to occur further offshore. This greatly affects the form of the resultant profile recorded on different beach slopes, under the same wave conditions. As breaking occurs, a 'surf zone' is created in which the wave height decreases progressively as waves approach the shore. When we compare the Condition I constant water depth experiments undertaken on the 1/7 and 1/9 gradient slopes, the smaller slope exhibited a wider central erosion area whilst the steeper beach showed a very small but deep plunging trough with a second area of erosion on the uppershore. As the breaking zone is smaller on the steeper beach, the larger waves can not dissipate enough energy in the plunging trough alone and so spill over in the uprush causing secondary erosion on the upper shore.

Under the larger wave height, the effect of initial beach slope on the resulting profiles is more noticeable. Offshore motion was clearly observed on the 1/7 beach under Condition II whilst on the 1/7 beach an onshore / swell profile resulted.

It may be noted that whatever the incoming wave height, the steeper beach is always more likely to exhibit offshore directed sediment transport. This is due to several reasons, some of which are listed below:

1) Waves break further offshore with a shallower slope, thus the incoming wave energy is reduced.
2) The undertow velocity increases with beach slope. Undertow and the gravitational force are the main contributors to offshore transport. MASSELINK and BLACK (1995) noted that on steeper slopes, where the wave height is less attenuated, larger height to depth ratios of the broken waves result and the bed return flow velocities are much larger.
3) An increased slope will lower the velocity required for the threshold motion, as the beach angle becomes closer to the inherent particle angle of repose. The natural reaction to a steep slope would therefore favour downward motion.
4) The greater reflection of steep beaches also increases the capacity of the waves to transport sediment offshore.
5) HORN and MASON (1994) also noted that the amount of suspension in the backwash was influenced by the water depth of the backwash. The breaking waves put most of the sediment into suspension and the swash moved the suspended sediment up the beach. The sediment appeared to remain in suspension in the backwash if the water depth was sufficient, so that it did not settle out before the backwash began. Thus, on a steeper beach where the settling depth is deeper, the sediment will remain suspended for longer and would therefore be more likely to be removed offshore by the undertow.

Alteration of beach slope

With an initial beach slope set to 1/7 or 1/9, it was noted that at the end of each tidal experiment the overall gradient of the beach slope had changed. This was not found with the constant water depth experiments. Many authors have noted that the beach slope is controlled by the wave and sediment characteristics. Greater wave steepness will cause offshore motion, while larger sized sediment increases the beach permeability. Increasing beach permeability will result in greater swash asymmetry. Water percolates much more rapidly into larger sediment than into smaller sized sediment. The result being that the return backwash on a coarse grained beach is weakened, thus encouraging onshore motion. Thus lower wave energy beaches with coarser sediments will have greater slopes. Table 2 gives a list of the beach slopes measured at the end of each tidal experiment. It can be seen that the 1/7 slope beach showed a decrease in beach slope whilst the 1/9 slope beach exhibited an increase in beach slope. The net change in the beach slope also depended on the wave condition.

Several authors have attempted to provide predictions of beach slopes in relation to the wave climate. These predictions assume that the beach has reached an equilibrium for a given wave condition. Some of these predictions are included in Table 2 for comparison with current measurements. Even though present results were not taken without the beach reaching an equilibrium, it is certain that an equilibrium beach slope is between 1/8.3 and 1/7.4 under Condition I and between 1/8.1 and 1/8.6 under Condition II. The predicted beach slopes are significantly greater than those found from the current experiments under Condition I but the predictions of NAYAK (1970) and SUNAMURA (1984) for Condition II are in line with the findings of this study.

CONCLUSIONS

The inclusion of tide in a beach model has been shown to significantly influence beach evolution. The end profile after a full tidal cycle shows very different characteristics from those observed under constant water conditions. Key conclusions are as follows:

- The beach profiles attained under the constant water depth represent those found at high tide during the tidal experiments.
- The way in which the tide affects the beach movement depends on the initial beach slope as well as the wave climate. Under storm conditions, a rolling bar was clearly seen moving below the SWL with both the flood and ebb tides. Under swell conditions on the flood, sediment was eroded once a critical depth had been reached but was moved onshore in the uprush to form the berm.

Table 2. Mean beach slopes at the end of a tidal cycle

	1/7 slope	**1/9 slope**	**DALRYMPLE et al (1976)**	**NAYAK (1970)**	**SUNAMURA (1984) In KOMAR (1998)**
Condition I	1/7.40	1/8.27	1/5.1	1/5.9	1/7.1
Condition II	1/8.08	1/8.6	1/5.9	1/8.4	1/8.3

- Beach models without the tidal component produce an incomplete description of the beach profile evolution. The constant water depth experiment for the 1/7 slope beach under wave Condition I predicted a net onshore transport but the tidal experiment showed that there was a net overall offshore sediment movement, although some beach material was also moved to the top of the beach.

- The characteristic plunging trough commonly found under low wave energy and constant water depth conditions is removed under a tidal influence.

- The presence of the tide results in an increased size of the berm in a summer profile, and pushes the offshore bar further seaward in the winter profiles.

- The overall beach slope can increase or decrease under the combined action of the wave and tide, depending on the initial slope. Under both wave conditions, the 1/7 beach showed a decrease in slope while the 1/9 beach had an increase. An equilibrium gradient exists in accordance with the dominant wave condition. In contrast, no noticeable overall slope changes were observed in the constant water depth experiments.

ACKNOWLEDGEMENTS

Our appreciation is expressed to Mr Robert Gayler for technical assistance.

LITERATURE CITED

DALRYMPLE, R. A. and THOMPSON, W. W. 1976. Study of equilibrium beach profiles. *Proceedings of the 15th Coastal Engineering Conference, ASCE*, 1277-1296.

DEAN, R. G. 1973. Heuristic models of sand transport in the surf zone. *Proceedings of the 1st Australian Conference on Engineering dynamics in the surf zone*, pp 208 – 214.

HORN, D. P. and MASON, T. 1994. Swash zone sediment transport modes. *Marine Geology*, 120, 309-325.

HUGHES, S. A. and CHIU, T. S. 1981. Beach and dune erosion during severe storms. *Coastal and Oceanographic Engineering Department, University of Florida, Report No. UFL/COEL/TR/043*.

KOMAR, P. D. 1998. *Beach processes and sedimentation*. Second Edition. Prentice Hall, 270p.

MASSELINK, G. and BLACK, K. P. 1995. Magnitude and cross-shore distribution of bed return flow measured on natural beaches. *Coastal Engineering*, 25, 165-190.

NAYAK, J. V. 1970. *Equilibrium profile of model beaches.* University of California, Berkeley. PhD Dissertation.

POWELL, K. A. 1990. Predicting short term profile responses for shingle beaches. *HR Wallingford Laboratory Report*, SR 219.

SHE K., POPE D and TRIM L, 2000. Mixed and shingle beach processes. *EPSRC Project Final Report (GR/L83264/01)*, School of the Environment, University of Brighton.

SUNAMURA, T. 1984. Quantitative predictions of beach-face slopes. *Geological Society of America Bulletin*, 95, 242-245.

WRIGHT, L. D and SHORT, A. D. 1983. Morphodynamics of beaches and surf zones in Australia. *In*: KOMAR, P. D. (ed.), *Handbook of Coastal Processes and Erosion*, Boca Raton, FL: CRC Press, 35 – 64. .