# CHAPTER 233

## BEACH EVOLUTION UNDER RANDOM WAVES.

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## ABSTRACT

This paper considers the evolution of steep mobile sediment beaches under random waves and results from a new experimental investigation are presented. Both hydrodynamic data obtained over fixed beds and the resulting profile evolution of fine, coarse and bimodal sediment beaches are discussed. Wave heights and undertow in the inner surf zone are found to be poorly predicted by commonly used numerical solutions. In addition, the undertow appears to be strongly influenced by wave grouping in the nearshore. The behaviour of the fine, coarse and bimodal sediment beaches are compared and contrasted. The fine sand beaches tend to erode in the inner surf and swash zones, with the sediment moving predominantly offshore to form a bar. In contrast, onshore sediment transport dominates over the coarse sand beaches, resulting in the formation of a berm above the initial still water level. The bimodal beaches show a similar evolution to the fine sand beaches. However, considerable sediment sorting occurs, with the swash zone largely denuded of fines and the coarser sediment deposited between the still water line and the bar. The data suggests that the stability of the coarse material is significantly reduced by the presence of fines, with little evidence of armouring effects under high incident energy conditions.


## 1) INTRODUCTION

The hydrodynamics within the nearshore region and the subsequent evolution of beaches under wave attack are important elements governing the stability of the coastal zone. However, numerical modelling of these processes has yet to result in consistent and realistic predictions of beach behaviour. The present

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study addresses this issue and considers two key aspects of the problem; the undertow and the sediment particle size. The time mean flow, or undertow, is considered one of the dominant mechanisms in the erosion of beaches (Svendsen, 1984). However, particularly under random waves, significant difficulties remain in the modelling of the undertow. This may in part be due to the difficulties in successfully predicting the wave motion in the inner surf zone (Hamm et al., 1993). In the present study, a comprehensive series of measurements of both the wave heights and near bed horizontal velocity are compared to a deterministic numerical model of nearshore processes (Southgate and Nairn, 1993).

Sediment size has a significant effect on both the magnitude and direction of sediment transport under wave action but the mechanics of the process are still poorly understood. Recent work by Work and Dean (1991) considered the effects of varying grain size on equilibrium beach profiles and showed that steeper profiles were found on beaches with larger grain sizes. However, most beaches exhibit a range of grain sizes, with frequent cross-shore sorting of sediment sizes. Moutzouris (1991) found that the coarsest sediments on a beach were generally found just seaward of the shoreline, while the finest sediments tended to be deposited on offshore bars. Mechanisms for this process have been considered by a number of authors (see Horn, 1991), but numerical models have so far resulted in little success.

Bimodal sediment transport under unbroken waves over a flat bed was considered by Mansell (1992). This work indicated a transient process, whereby the winnowing of fine grains from the bed surface led to the formation of a coarse armour layer. Using model beaches, Quick and Dyksterhuis (1994) found some evidence of an armouring process at low energy conditions. In contrast, at higher energy conditions the coarser sediment had little effect on the profile evolution and the fines controlled the beach steepness. The beach permeability therefore appeared to have a controlling influence on the beach behaviour. However, previous experimental work has not considered the sediment sorting process on beaches and, in particular, the cross-shore distribution of sediment sizes. The present study considers this process and identifies key features that appear consistent with field observations.

## 2) HYDRODYNAMICS

The experiments were carried out in a large wave flume in the Civil Engineering Department at Imperial College. This flume is 60m long, 3m wide and was used with a working depth of 0.9m. Waves are generated by a hydraulically driven bottom hinged paddle with the facility to absorb wave components reflected from the far end of the flume. The end of the flume is subdivided into three sections to minimise cross-tank motions and consists of a composite beach, with an initial slope of approximately 1/20, rising to 1/10 at the shoreline. Jonswap spectra with three different significant wave heights and wave periods were used (table 1). Data was collected over 330s at 25Hz, giving 8192 points in each run. The water surface elevation was measured with standard surface piercing resistance type wave gauges and the wave heights calculated form the zeroth spectral moment ($Hrms=\sqrt{(8m_0)}$). The horizontal velocity 6mm above the fixed bed was measured using LDA and an acoustic Doppler velocitymeter (ADV). The ADV was less sensitive than the LDA to noise from air bubbles generated by breaking waves, and allowed velocity data to be obtained in very shallow water.

| Spectrum | *Hrms* (mm) | $f_p$ (Hz) | $T_z$ (s) |
|---|---|---|---|
| L | 90 | 0.68 | 1.47 |
| P | 70 | 0.68 | 1.47 |
| K | 45 | 1.0 | 1.0 |

**Table 1**. Random wave spectral characteristics.

**Wave heights**

Figures 1a&b shows the *Hrms* wave height across the surf zone for cases P and K respectively. In the outer surf zone, the numerical solution (based on the Battjes and Janssen (1978) approach) gives good results. However, in the inner surf zone the variance and, consequently the wave height, does not decrease to zero at the shoreline. Indeed, the wave height only reduces to about half that of the initial offshore wave height. This is because the steep beach slope allows waves to travel close inshore before breaking and forming bores. The set-up just shoreward of the initial shoreline position is found to be small (of order 5mm) and this is therefore not the reason for the observed increase in wave height in the inner surf zone. It is interesting to note that calculations of the wave height based on the spectral approach and a zero crossing analysis give very similar results in the inner surf zone. This is despite the fact that the wave heights frequently exceed the water depth.

The measured spectra for case P are shown on figure 2, together with the smoothing interval and 95% confidence limits. Offshore of the breaker zone there is little energy in either the lower or higher harmonics, while just seaward of the initial shoreline the energy in the lower harmonics increases significantly. This is expected due to the generation of non-linearities by the shoaling process and the amplification of low frequency waves in shallow water. There is also a small frequency downshift of the spectral peak. However, the spectrum close to the shoreline is still dominated by energy close to the initial spectral peak frequency. The inner surf zone spectra are therefore significantly different from those observed on low slope beaches, where low frequency energy often dominates (e.g.

Holland et al., 1995). The present data are consistent with both the measured wave heights and the formation of bores with a frequency close to $f_p$.

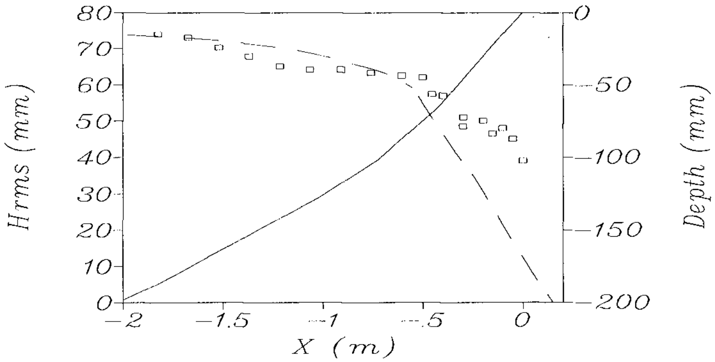



**Figure 1a**. RMS wave height across the surf zone, case P.
——— Depth , □ □ □ □ Data points, — — — Numerical solution.

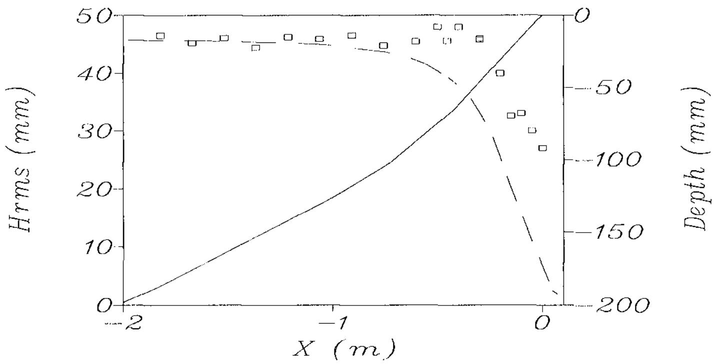



**Figure 1b**. RMS wave height across the surf zone, case K.
——— Depth , □ □ □ □ Data points, — — — Numerical solution.

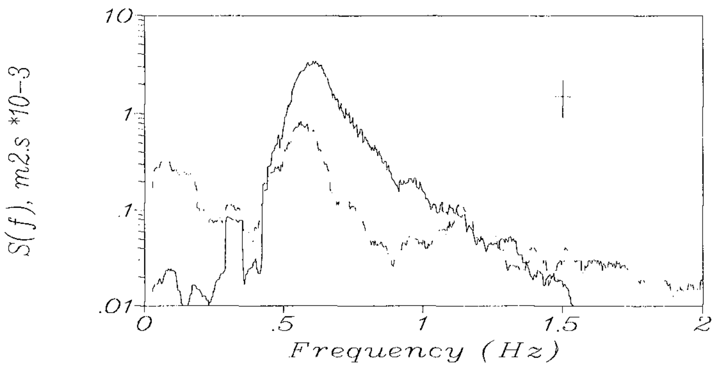



**Figure 2**. Wave spectra for case P outside the surf zone and close to the shoreline.
———— x=-2m (d=200mm), – – – – x=-0.05m (d=10mm).

## Undertow

The time-mean flow, or undertow, averaged over the total run time is shown in figures 3a&b. For both cases P and K, the undertow in the outer surf zone is very well predicted. However, for case P, the maximum value of the undertow is over-estimated but the undertow close to the shoreline is under-predicted. The over-estimation of the maximum is probably due to the difficulty in determining the depth over which the forward mass flux should be averaged and the less well defined breakpoint (see figure 1a). In shallow water, and particularly with a significant degree of turbulence, it may be more realistic to average the mass flux over the mean water depth, rather than just below trough level as is usual (e.g. Svendsen, 1984). The under-estimation of the undertow in the inner surf zone is consistent with the presence of larger waves than predicted by the numerical solution. A similar effect may be observed for case K (figure 3b), where, in addition, the principal breakpoint is also closer to the shore than predicted (figure 1b). This is likely to increase both the maximum value of the undertow and the undertow close to the shoreline. It therefore appears that a more realistic model for the nearshore wave heights is required for beach slopes of this steepness.

Recent field measurements have suggested that suspended sand concentrations are strongly correlated with the occurrence of wave groups (e.g. Hay and Bowen, 1994). This prompted a closer examination of the velocity field beneath the random waves used in the present investigation. The measured Eulerian horizontal velocity, averaged over either one or three wave periods, shows significant variations in the "local mean" flow, which may be an order of magnitude greater than the long term mean. Figure 4 shows the velocity averaged over three wave periods, the wave height averaged over the same time period and the long term mean velocity.

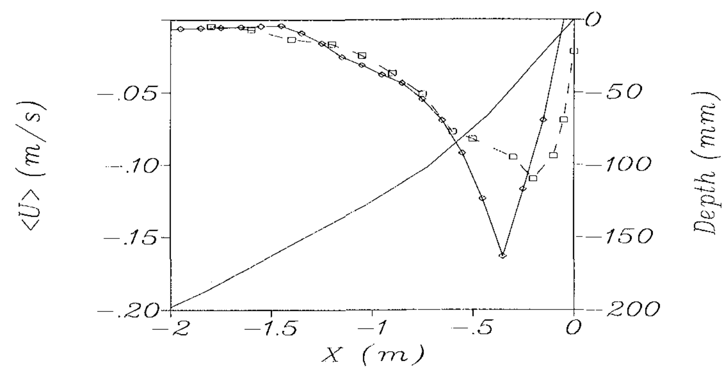



**Figure 3a.** Undertow. Case P.
——— Depth, – □ – data points, —◇— Numerical solution.

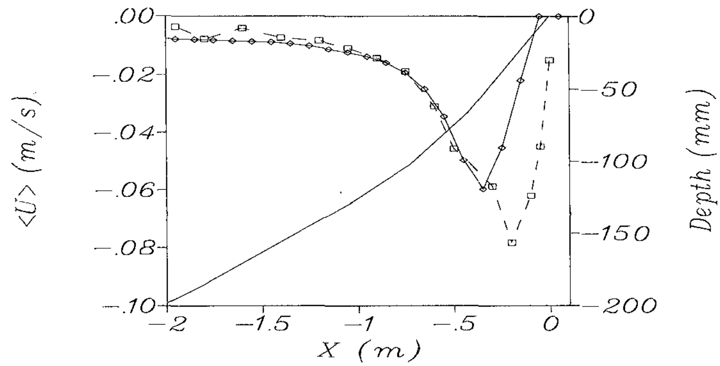



**Figure 3b.** Undertow. Case K.
——— Depth, – □ – data points, —◇— Numerical solution.

The variation in the "local mean" flow is strongly correlated with the occurrence of incident wave groups, which suggests that the groupiness of the wave field may be an important feature in suspended sediment transport. Note that the sign of the mean velocity has been inverted to show the correlation with wave height more clearly. The data show that large onshore mean velocities generally occur during the passage of smaller waves, while offshore mean velocities are found under the largest waves. If these variations in the mean flow are combined with coherent fluctuations in the concentration of suspended sediment, then a much large volume of sediment may be moved in suspension than a volume based on the product of the mean velocity and mean sediment concentration.

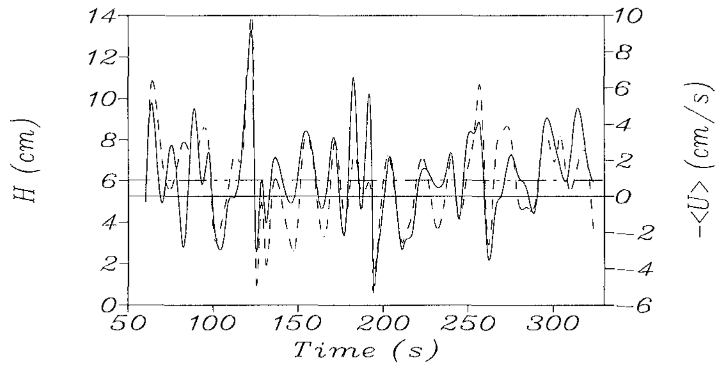



**Figure 4.** Temporal variations in the "local mean" flow. Case P.
——— Wave height, – – – – "local mean" flow (inverted),
— ·· — long term mean, <U> (inverted).

### 3) Beach evolution

Beach evolution experiments were carried out under random waves for a fine sand beach, a coarse sand beach and a bimodal sediment beach. In order to facilitate the experimental study, the sediment sizes needed to satisfy three criteria:

1. Both sediment sizes should be mobilised by the maximum velocity in the inner part of the surf zone.
2. The ratio of the two sizes should be large enough to result in significantly different profile evolution as well as allowing them to be readily separated from the bimodal mixture.
3. Each sediment should be well-sorted so as to produce the bimodal characteristics in the resulting grain size distribution of the mixture.

Using these criteria, the sediment size for the coarse and fine sand respectively were chosen to be $D_c$= 1.5 mm and $D_f$= 0.5 mm. The grading curves for the two sands and a 50:50 mix are shown in figure 5. Sediment beds with a thickness of 100 mm were laid over the existing solid beach and the water level in the flume raised by the same amount, resulting in the same initial beach profile as used while collecting the hydrodynamic data. The profile evolution experiments were conducted for a total duration of 240 minutes, using repeated 30 minute runs of the spectra shown in table 1. The flume was allowed to settle after each 30 minute run and there was no evidence of the build up of significant seiching due to wave reflections. The experiments were carried out on the coarse and fine grained beaches separately to serve as controls and to provide comparison with the evolution of the bimodal beach.

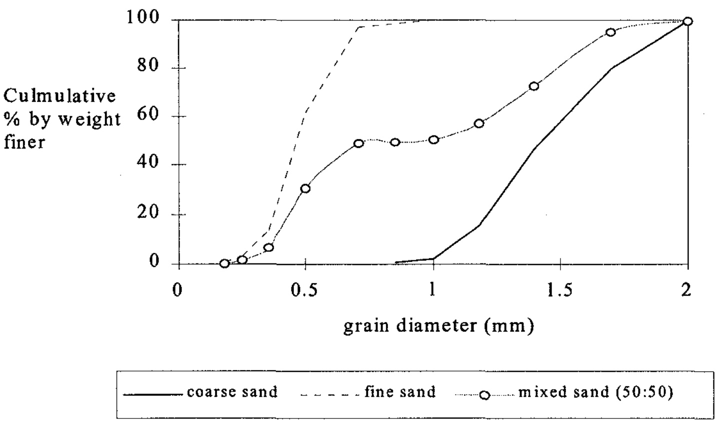
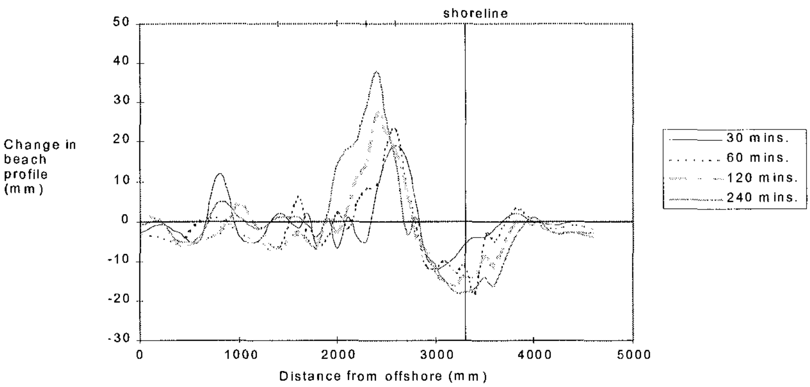



**Figure 5**. Grading curves.

## Profile evolution with uniform sediment size

Several general observations apply to the beach profile evolution for each of the three spectra. Firstly, the coarse sand beaches tend to form a distinct berm shorewards of the initial SWL. The berm appears steepest for case P, which has the lowest deep water wave steepness. For the fine sand beaches, the formation a bar flattens the beach slope in the surf zone. Seaward migration of the bar was evident and the bar moves further offshore as the wave height increases. The SWL recedes shoreward in all cases, except for the coarse beach using case P. Examples of the cross-shore changes in bed level are shown on figures 6&7. A predominant onshore transport is observed in the case of coarse sand while the fine sand bed suffered much erosion around the shoreline, with sediment transported offshore to form a bar.

**Fine sand**




**Coarse sand**

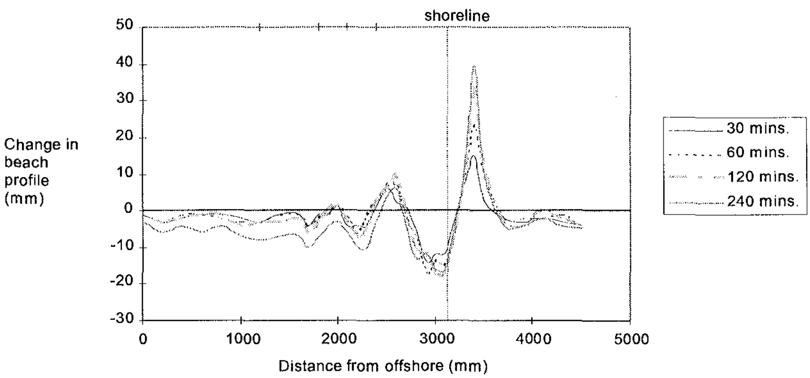
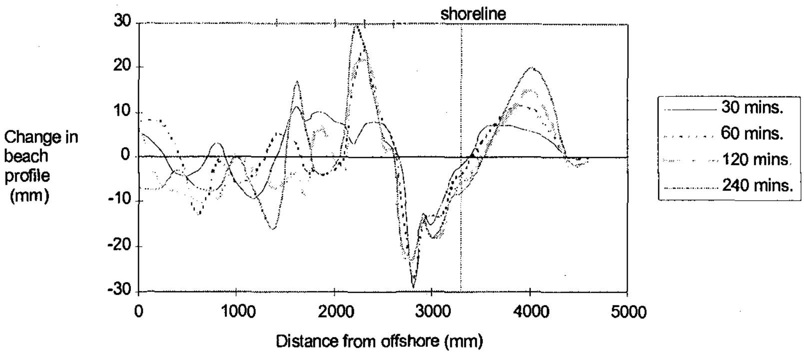



**Figure 6**. Change in bed elevation from original profile, case K.

**Fine sand**




**Coarse sand**

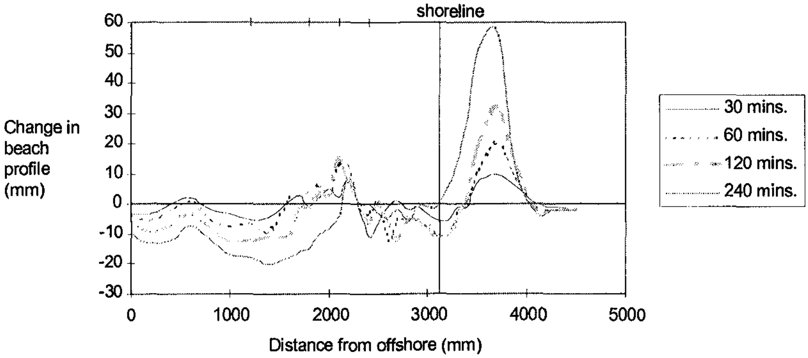



**Figure 7.** Change in bed elevation from original profile, case P.

## Bimodal sediment sampling methods

A 50:50 mix of coarse and fine sand was chosen for the bimodal beach. Two sampling devices were used to determine the changes in the composition of the bimodal beach after wave action. The first was a 25mm square spot sampler, which was used to take sediment samples along the centre line of the bed. The second was an in-situ section sampler, placed in position before laying the beach and used to lift whole sections of the bed material from the beach. The section sampler allowed a section of the bed to removed with minimal disturbance of the sample and enabled the vertical section of sediment sample to be analysed layer by layer (with layers as small as 5 mm). A calibrated fall tube was employed to sort the sampled material, allowing the change with depth in the mix ratio of the beach material to be ascertained. Further details of the sampling method will be available shortly in the Ph.D. thesis of R. T. C. Chan. In order to establish the variability of initial bed composition a trial experiment was performed to sample the bimodal beach after it was laid. The sampling procedure included taking a section of the bed out (using the section sampler) at six different locations on the beach and 10 layers, each of 5 mm thick, were analysed at each location. The mean in-situ initial mix ratio was found to be 0.515 (coarse/total), with variations of less than 1% by volume between the different locations.

**Profile evolution with bimodal sediment**

Comparisons of the final beach profiles (after 240 minutes of wave action) for the fine, coarse and bimodal beaches are shown on figures 8a&9a for cases K and P respectively. The original profile in each case is also shown as a reference. The numbered circles at the top of each graph indicate the locations of the section samplers. Figures 8b&9b show the change in bed level from the original profile, where the positions of the section samplers are shown by the numbered triangles. The variation of the mix ratio (coarse/total) with depth at different sections of the beach is shown on figures 8c&9c. The experimental data show several features of particular interest.

In the inner surf zone and swash zone, the final profiles for the bimodal beach resemble the fine sand profiles much more closely than those for the coarse sand. This is the case for all three wave spectra and is confirmed by the bed level changes (figures 8b&9b). The bar positions on the bimodal beach are shoreward of those found in the fine sand beach. Recalling that a seaward migration of the bar was observed on the fine sand beach, it is apparent that there is a tendency for the coarse sand to curb the bar from migrating offshore. On the bimodal beach, the surface of the shoreward slope of the bar is dominated by coarse sediment (refer to section 4a on figures 8c and sections 4,5 and 6 on figure 9c). This is in marked contrast to the higher proportion of fines found on the seaward slope of the bar (section 4b on figure 8c, section 7 on figure 9c). Finally, the foreshore (just above the SWL in the lower swash zone) of the bimodal beach tends to be denuded of coarse sand (sections 2 and 3 on figures 8c&9c).

In summary, the results show that, although the bimodal sediment beach behaves in a similar fashion to the fine sand beach, in agreement with Quick and Dyksterhuis (1994), considerable sediment sorting has also been observed. The present data show that the region between the shoreline and the bar tends to be dominated by the coarse sediment. This appears consistent with the field data of Moutzouris (1990), which showed that the largest grain size often occurred just seaward of the shoreline. Within the swash zone, the fine sand within the mixture seems to destabilise the coarser sand. This facilitates the erosion of coarse sand on the foreshore, and is most conspicuous at the position of the steepest slope. A similar process is also evident on the seaward slope of the bar. This suggests that the mobility of the coarse sand in the mixture is substantially increased due to a greater exposure and a reduction in friction in the presence of fines. This appears consistent with the results of Miller & Byrne (1966), who found that there is a reduction of the angle of repose when large grains sit on a bed of smaller grains.

The difference in the evolution of the fine and coarse sand beds may be due to a combination of factors. The most dominant are probably a different threshold condition and a difference in the permeability of the beach material. A higher threshold condition for the coarse sand will tend to result in a greater net shoreward transport of sediment. The high permeability of the coarse sediment is also likely to lead to greater infiltration within the swash zone, reducing the backwash and leading to or increasing the asymmetry in the swash zone velocities. This hypothesis is consistent with the much larger berm formation observed on the coarse beaches. In contrast, the bimodal beach permeability will be largely controlled by the finest 10% of sediment within the mix (e.g. Hazen, 1892). Consequently, both the fine sand beaches and the bimodal beaches have a similar permeability. Since both beaches evolve similarly, the permeability appears to be the dominant controlling factor, as suggested by Quick and Dyksterhuis (1994). This has important implications for both numerical modelling of swash processes and beach recharge schemes. For example, if the fines control the beach permeability, and as a consequence the beach behaviour, the addition of coarser supposedly more stable sediment may have little effect on the overall stability of the beach. On the other hand, if the permeability is a controlling factor, beach drainage should be an effective method of beach stabilisation, although some questions remain as to its effectiveness.

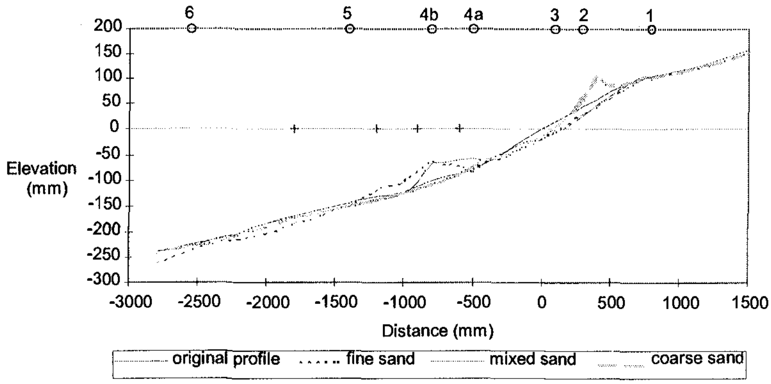



**Figure 8a**. Profile evolution after 240 minutes, case K.

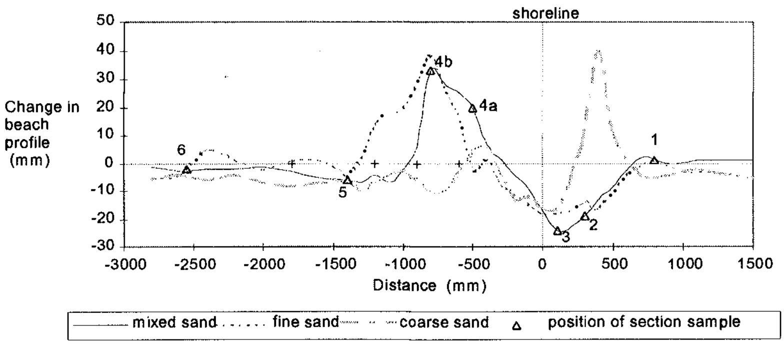



**Figure 8b**. Change in bed elevation from original profile, case K.

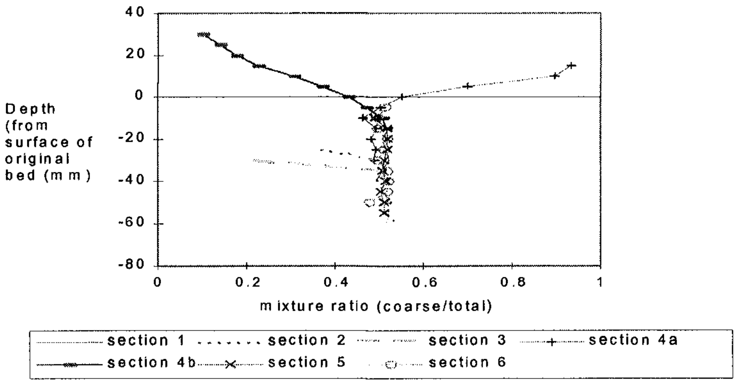



**Figure 8c**. Variation in mix ratio with depth at six cross-shore locations, case K.

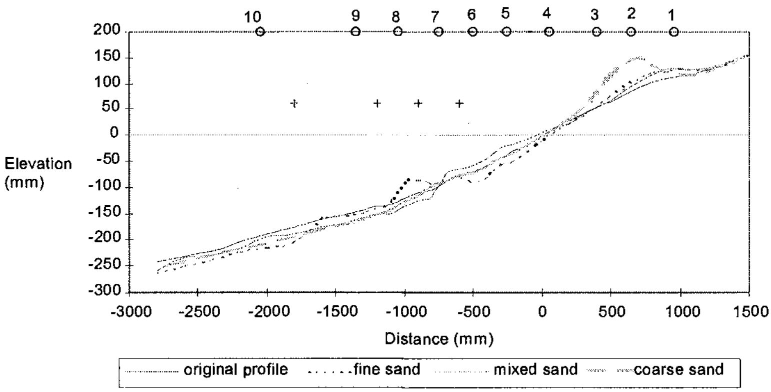



**Figure 9a**. Profile evolution after 240 minutes, case P

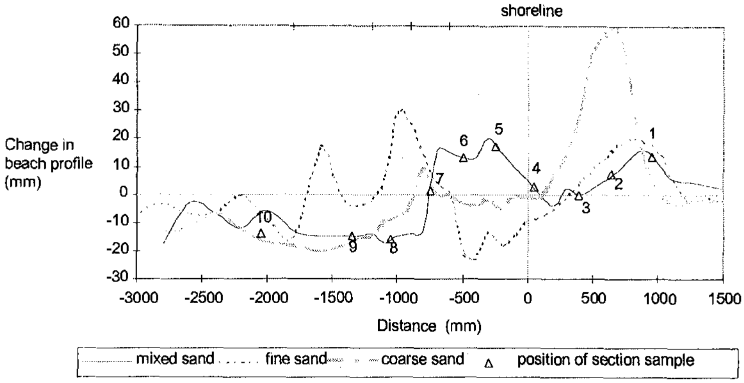



**Figure 9b**. Change in bed elevation from original profile, case P.

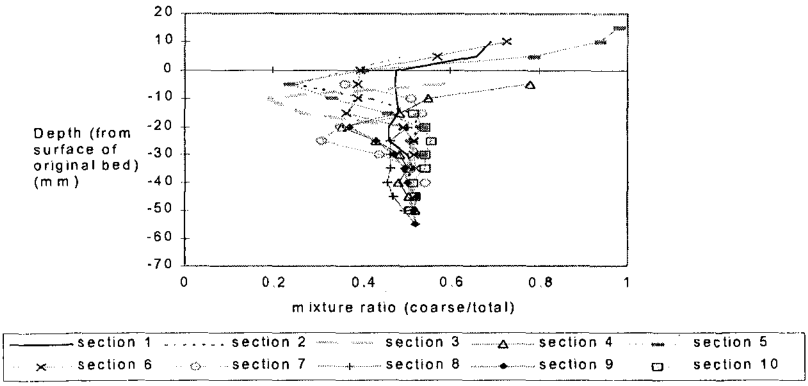



**Figure 9c**. Variation in mix ratio with depth at six cross-shore locations.

## CONCLUSIONS

The results of a new experimental investigation have been presented. Hydrodynamic data obtained over a steep fixed beach show that the wave heights and undertow in the inner surf zone are under-estimated by the numerical solution. In particular, the wave heights in the inner surf zone are not depth limited to the expected degree. This is a consequence of the steep beach slope, with insufficient time for wave breaking fully to establish. Significant wave grouping is evident in the nearshore. This leads to large local fluctuations in the "mean flow", which are strongly correlated with the wave groups. The profile evolutions of fine and coarse sediment beaches were found to be very different, with the fine sand beaches tending to erode to form a bar, while the coarser beaches generally accreted, resulting in the formation of a berm. The profile evolution of bimodal beaches was found to be similar to that of fine sand beaches, although considerable sorting was observed. The data suggest that the permeability of beaches is of particular importance, in agreement with some previous studies. The presence of fines appeared to destabilise the coarser material within the bimodal beach, with little coarse material present on the bed surface in the swash zone and on the bar crest. In contrast, the coarse material appeared to have little effect on the movement of the fine sediment, with little evidence of armouring. Clearly there is a need further to investigate the influence of the fine/coarse ratio in bimodal sediments and to consider continuously-graded sediments.

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