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# SID 5 Research Project Final Report

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## Project identification

1. Defra Project code: FD 1923
2. Project title: Influence of permeability on the performance of shingle and mixed beaches
3. Contractor organisation(s): University of Brighton
   Civil Engineering Division
   School of Environment
   Lewes Road
   Brighton BN2 5GJ
4. Total Defra project costs: £ 48,374
5. Project: start date ................ 15 February 2005
   end date ................ 14 February 2006

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Please confirm your agreement to do so.................................................................................. **YES** ☒ **NO** ☐

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## Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

### Background

Beach recharge using mixed sand-gravel sediment is a common practice in the UK as a means of coastal defence and protection against storm wave attacks. Good design of beach recharge schemes involving mixed sand-gravel sediment depends on effective means of predicting the behaviour of the beach in response to different wave conditions. Such predictive means in turn depends on our understanding of sediment processes on mixed sand-gravel beaches. At the present time, it is generally accepted that the presence of sand significantly alters the hydraulic conductivity (permeability) of the beach, but until now there has not been a systematic study of the impacts of the reduced permeability on the performance of the beach. A particular problem associated with recharged sand-gravel beaches is the development of cliffing on the upper foreshore, which can be hazardous to the public.

The engineering demand for effective predictive methods, and clear gaps in our knowledge of mixed beach behaviour, lead to an urgent need to conduct a comprehensive review of the current state of knowledge in relation to the hydraulic conductivity and performance of mixed sand-gravel beaches, and to identify future directions of research. This scoping study investigates issues such as the influence of permeability on the performance of recharged beaches, the development and prevention of cliffing, sediment resources and their management, efficiency of sediment placement techniques, and cost effectiveness of frequent and focussed recycling operations. The specific objectives are as follows:

- to produce a review of existing knowledge of the impacts of permeability on the performance of gravel and mixed sand-gravel beaches;
- to investigate the cliffing problem of recharged mixed sand-gravel beaches;
- to examine the effects of the sand fraction on the permeability and porosity of mixed sand-gravel sediment, and the ways forward in alleviating the problem of cliffing;
- to carry out numerical modelling to improve understanding of the effect of permeability on beach profile response on mixed beaches, including the relative importance of parameters such as hydraulic conductivity, wave friction factor, sediment grading, and groundwater flow;
- to propose recommendations for a framework of field and laboratory studies to advance knowledge of the influence of permeability on beach performance.

### Results

The scoping study takes the form of an extended literature review; theoretical analysis coupled with special purpose laboratory experiments; re-analysis of existing experimental data; numerical modelling with the support of laboratory and field data; and case studies of three current/recent beach recharge programmes and related aggregate resource.

The literature review shows that no standard method is yet available for characterising mixed sediments. A primary difficulty is that mixed beaches exhibit a high degree of variability, both spatially and temporally, in terms of sediment size and density, sediment shape, sorting, hydraulic conductivity, porosity, specific yield and moisture content. It seems, however, that the percentage of sand and its size relative to the gravel are among the most important parameters associated with the performance of a mixed sand-gravel beach, and thus may be used as key parameters characterising mixed beaches. The literature also indicates that sediment transport is affected by the relative proportions of sand and gravel.

Limited laboratory experiments show that under the same wave conditions, mixed sand-gravel beaches have reduced volumetric changes, less onshore transport, and more offshore transport than gravel beaches. This may be directly related to the fact that the presence of sand in a mixed beach significantly reduces the permeability of the beach, impairing the water flow within the sediment media. Laboratory experiments and numerical modelling also show that altering beach groundwater levels affects profile response on fine and coarse beaches, with a greater amount of change on coarse beaches. A lower groundwater level leads to increased onshore transport and a higher groundwater level to increased offshore transport for both accretionary and erosional conditions.

The cliffing problem of recharged mixed sand-gravel beaches was firstly investigated by means of a simplified theoretical model of mixed sediment. The theoretical analysis led to a group of simple equations that relate the porosity, hydraulic conductivity and bulk density of the mixed sediment to the percentage of sand in the sediment. A series of laboratory experiments were then carried out which successfully validated the theoretical equations. The hydraulic conductivity of the mixed sediment was shown to be greatly influenced by the presence of sand. The equations also provide an indication of the worst scenario in terms of the likelihood of cliffing, and how compaction affects the hydraulic conductivity and cliffing of a recharged sand-gravel beach. The theory suggests that the cliffing problem may be significantly alleviated by controlling the sand percentage, which should not exceed the critical value corresponding to a given sand and gravel size (normally in the range of 30% to 40%). It was also noted that the control of the sand percentage is only required for the upper beach, or just the beach crest, and it is achievable through managed use of sediment sources and/or improved sediment placement techniques.

Limited numerical modelling shows that the hydraulic conductivity of the sediment and the groundwater level both have significant effects on the evolution of the beach surface. Model simulations suggest that accretion on the upper beachface increases with increasing hydraulic conductivity. There is a clear need for improved numerical models specifically designed to deal with mixed beaches.

The case studies included three sites: Pevensey Bay in East Sussex, Tankerton in Kent and Hayling Island in Hampshire. The analysis of the data collected from the three sites highlights the importance of frequent and focused recycling operations and the widespread problem of cliffing. At the Pevensey Bay site, the volume of annual recycled material is of the same order as the annual maintenance recharged material, leading to significantly reduced operational cost while improving the efficiency of use of limited sediment resources. The field data also show that the high sand percentage coupled with an unnaturally steep beach slope seems to be the predominant cause of the cliffing problem. Laboratory and field evidence indicates that a natural slope of a mixed sand-gravel beach is around 1:9, but recharged beaches tend to have a design slope of ~1:7. The experiences from these three sites indicated that reducing the sand percentage at the upper beach had the positive effect of alleviating the cliffing problem.

For economic reasons and sustainable development, the efficiency of aggregate production has to take precedence over the quality of its production. This means that a greater emphasis has to be placed on the improvement of placement and mixing techniques of the aggregate at the point of delivery. The modified rainbowing technique of Pevensey Coastal Defence Ltd is worth more investigation and may be considered for wider applications. In a typical deposition mound, the fine material tends to migrate furthest from the point of discharge, with the coarser sediment remaining in the centre of the mound. Sampling of recharge mounds showed a clear spatial separation in sediment distributions within the mounds, making it possible to identify the most suitable locations for recovery of coarse sediment for placement on the beach crest.

The research has shown without any doubt that the performance of a recharged mixed sand-gravel beach is closely related to the hydraulic performance of the beach. A mixed sand-gravel beach is likely to suffer much greater damage than a gravel beach of the same median sediment size.

A number of recommendations for future work are produced and these are given in the Project Report below. The recommendations are grouped in terms of types of work/study and relevant groups of interest. Priorities of the recommendations are also suggested to aid the decision making for future research and development.

**Outputs and their use**

The main outputs from this scoping study are 1) the Technical Report, 2) a paper at ICCE 2006, 3) a paper at the Defra Conference 2006, 4) a Defra newsletter, and 5) five Internal Project Reports.

In addition, a paper was submitted to *ASCE Journal of Waterway, Port, Coastal and Ocean Engineering*, a paper was submitted to *Coastal Sediments 2007*, and other papers will be submitted in 2006 to *Coastal Engineering* and *Marine Geology*.

The Technical Report includes an extensive review of the current state of understanding of the mixed beach processes, the method of prediction of the cliffing problem, and preliminary advice on good practices in relation to beach recharge programmes.

## Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:
   - the scientific objectives as set out in the contract;
   - the extent to which the objectives set out in the contract have been met;
   - details of methods used and the results obtained, including statistical analysis (if appropriate);
   - a discussion of the results and their reliability;
   - the main implications of the findings;
   - possible future work; and
   - any action resulting from the research (e.g. IP, Knowledge Transfer).

**INTRODUCTION**

Recharged mixed sand-gravel beaches are a common means of sea defence in the UK. Field experiences have revealed a number of significant problems in relation to such schemes, including, critically, safety concerns as a result of cliffing. Cliffs of up to two metre height are common among newly recharged mixed beaches (Figure 1). These cliffs can be extremely hazardous due to their natural instability and may require removal at the first opportunity. This scoping study aims to investigate the influence of permeability on the performance of recharged beaches as well as issues such as cliffing, sediment resources and their management, efficiency of sediment placement techniques, and cost effectiveness of frequent and focussed recycling operations.

**Figure 1 Cliffing photographed at Hayling Island (left) and Pevensey Bay (right)**

The primary objectives of the project are

(a) To produce a review of existing knowledge of the impacts of permeability on mixed and gravel beach performance;

(b) To propose recommendations for a framework of field and laboratory studies to advance knowledge of the influence of permeability on beach performance.

In addition to the above objectives, the project team also aimed at achieving three secondary objectives:

(c) To develop a database of mixed sand/gravel beaches in England;

(d) To develop a methodology by which sediment properties on mixed sand/gravel beaches can be characterised;

(e) To carry out numerical modelling to improve understanding of the effect of permeability on beach profile response on mixed beaches, including the relative importance of parameters such as hydraulic conductivity, wave friction factor, sediment grading, and groundwater flow.

During the early part of the project, it became clear that one of the most significant concerns of the past and present beach recharge programmes was the cliffing problem. At the same time, an initial examination of the existing databases showed that it was unlikely that within the short time scale of the project a new database could be developed that would bring any desired improvements on the existing ones such as that of the Channel Coastal Observatory. At the Steering Group Meeting in October 2005, the secondary objective (c) was formally replaced by the following objective:

(f) To investigate the cliffing problem of recharged mixed sand-gravel beaches.

The investigation takes the form of an extended literature review, theoretical development coupled with laboratory experiments, numerical modelling with the support of laboratory and field data, and case studies of three current/recent beach recharge programmes. A full report of the research findings is given in the Technical Report and below is a summary of the main results.

## LITERATURE REVIEW

The literature review was intended to look at the current state of knowledge on mixed beaches and, in particular, the effects of permeability on gravel and mixed beach behaviour. Typical problems faced by those responsible for managing mixed beaches include the inability to determine the sensitivity of the beach profile and cross-sectional area to variations in sediment distributions, poor predictive capacity for cross-shore response of mixed sediment beaches to storms and their recovery after storms, uncertainty in predicting longshore or offshore losses of recharge sediment over time, inability to predict beach response in the vicinity of coastal structures, and inability to predict the importance of seepage through barriers. Some of the fundamental research questions and challenges identified by this review relate to

1) understanding the difference between coastal dynamics on mixed sand and gravel beaches and beaches dominated by relatively uniform sediment sizes (either sand or gravel)
2) examining possible methods that may be used to quantify and/or classify complex, spatially and temporally variable sediment characteristics effectively on mixed sand and gravel beaches
3) developing methodology to parameterise the effects of bimodal sediments and mixed sand and gravel in hydrodynamic and morphodynamic models

4) adapting existing numerical models to predict the processes and morphological evolution of mixed sand and gravel beaches

Below is a summary of key issues that arose from the review.

**Characterisation of sediment properties of mixed beaches**

Mixed beaches show a high degree of variability, both spatially and temporally, in terms of key parameters such as sediment size and shape, sorting, hydraulic conductivity, permeability, porosity, specific yield and moisture content. In particular, the amount of air contained in beach sediments is likely to vary across the beach profile and also temporally, at both tidal and wave frequencies, and can significantly reduce hydraulic conductivity. The degree of compaction, and hence porosity, of sediment is also highly variable, particularly in the swash zone. However, very few field measurements of these parameters have been reported in the literature.

No standard method is available for characterising bimodal sediments. The degree of bimodality and the nature of the mixture has been shown to be important in the initiation of motion, sediment transport, and beach profile evolution, and should be included in sediment parameterisation.

The percentage of sand in a mixture has been suggested as a simple indicator of the performance of a mixed beach. However, the percentage of sand on a highly mixed beach is not easy to determine and is probably not constant over time.

Properties such as sediment sorting, particle shape and packing have a major effect on porosity and sediment transport of mixed sediments; these are also highly variable on mixed beaches, but hard to reproduce in laboratory experiments.

**Sediment processes**

Sediment transport is affected by the relative proportion of sand and gravel. Evidence from field experiments suggests that a larger particle is more likely to be moved out of an area that is dominated by smaller well-sorted particles, whereas transport of smaller particles in an area of mixed sizes tends to be impeded by the larger particles. The velocity of coarse sediment in a mixture has been found to be higher than the velocity of uniform coarse sediment, and the transported sediment is coarser than the original mixture. However, the effect of fine sediment on very coarse sediment appears to be negligible when the diameter of the coarse sediment is more than four times the mean diameter of the sediment mixture. Beach profile evolution in laboratory experiments has also been shown to be affected by the relative proportion of sand and gravel.

The process of kinetic sieving (size sorting within the bed) is a mechanism by which finer grains are able to occupy space vacated by the entrainment of large grains, but not vice versa, leading to a downward movement of fine grains relative to coarse grains. This process leads to a gradual filling of pore spaces by fine sediment and a coarser surface layer, which is more easily entrained. The degree of size segregation appears to increase with increasing mixture bimodality.

Initiation of motion of mixed sediments is better understood under unidirectional flow than under oscillatory flow. Unidirectional flow studies indicate that the critical shear stress for initiation of motion of individual fractions in bimodal sediments depends on mixture bimodality. In sediments with a strongly bimodal distribution, fine grain sizes begin moving at measurably smaller values of bed shear stress. Mixture bimodality appears to affect fine fractions more than coarse fractions.

Model simulations suggest that bedload transport processes under waves segregate grains by size and density when the distribution of grain sizes is not uniform. Transport rates for different grain sizes can vary by factors of two to three or more for mixed size distributions. Simulated transport rates for uniform sediments are greater than those for mixed sediments. The single representative grain size whose bed load transport rate is equivalent to the mixed size distribution increased from $D_{75}$ under Stokes-like waves, to $D_{85}$ under near-breaking waves, to $D_{95}$ under a bore. These numerical experiments suggest that model results relative to heterogeneous sediment flux cannot be accurately quantified using a single representative grain parameter. Laboratory experiments under sheet flow conditions indicate that gradation effects on sediment transport rates cannot be predicted by the transport rate of uniform sediment.

**Profile evolution**

Laboratory experiments on profile evolution of mixed beaches suggest that results depend on the relative proportion of sand and gravel. However, most observations show that adding sand to a gravel beach destabilises the coarse beach, causing both the gravel and the sand to move offshore, producing a lower beach slope which is very similar to a sand beach. These results are analogous to those reported for mixed sediments under unidirectional flow. The assumption is that these results are due to the effects of reduced permeability, but this assumption has not been validated with direct measurements of hydraulic conductivity.

Laboratory experiments show that under the same wave conditions, mixed beaches have reduced volumetric changes, less onshore transport, and more offshore transport than gravel beaches. Model simulations suggest that subaerial beach volume is positively related to hydraulic conductivity and that accretion on the upper beachface increases with increasing hydraulic conductivity.

**Infiltration and exfiltration**

Infiltration loss in the swash is often given as the reason why gravel beaches are steeper than sand beaches. However, the effects of flows through the porous bed (vertical, horizontal and slope-parallel) on entrainment and sediment transport are not clear. The contradictory results reported in the literature may be because the main physical mechanisms by which flow through a porous bed affect sediment motion (seepage force and boundary layer thinning) tend to oppose each other. It has been suggested that the relative importance of these opposing effects depends on the density of the sediment and the permeability of the bed. For a fixed sediment density, as grain size (and therefore hydraulic conductivity) decreases, the stabilising effect will increase. Infiltration is likely to enhance sediment mobility for dense coarse sediment and impede sediment motion for light, fine sediment. However, this analysis has not yet been extended to mixed sediments.

When waves propagate over a porous bed, fluid flow is induced in the porous medium and the porous medium itself may be deformed. Three main processes have been identified regarding the interactions between flows outside and within the sediment bed, all of which can have varying effects on sediment motion across the beach:
(1) vertical pressure gradients due to infiltration;
(2) horizontal pressure gradients due to the set-up and run-up; and
(3) liquefaction due to repeated cyclical wave loading on the sediments.

Model simulations of the effects of infiltration/ exfiltration, and the inferences drawn from this modelling about infiltration effects on beach profile evolution, are based on theory which has not yet been verified in terms of swash zone sediment transport. Although some of these simulations have been driven by measurements of pore pressures in natural beaches, simulations of sediment transport and/or beach profile response have not yet been validated against either laboratory or field data. In particular, no studies of this sort have yet been carried out for mixed sand and gravel beaches.

**Internal flow and hydraulic gradients**

Very few measurements have been reported of hydraulic gradients on mixed beaches, and the relative importance and magnitude of flows within mixed beaches is yet to be determined. The few reported measurements indicate that hydraulic gradients and flows within mixed beaches are less than those on pure gravel beaches. Pressures appear to propagate through a gravel beach nearly instantaneously and are very nearly hydrostatic. This suggests that particles on a gravel beach are only acted on by flow forces, whereas on a mixed beach pressure gradients must be taken into account in order to predict profile evolution.

**Wave reflection**

Few measurements of reflection from mixed beaches have been reported in the literature, and it has not yet been possible to determine whether changes in reflection coefficients on mixed beaches are due to sediment properties or simply due to the well-known increase in reflection on steeper slopes.

**Numerical models**

Existing gravel beach models have not been validated for mixed sand and gravel beaches, and the limited tests of these models suggest that use of these models for mixed beach profile evolution cannot be predicted by simply modifying and recalibrating existing sand or gravel beach models.

At present, no existing sediment transport model contains all of the significant factors in mixed sediment transport. Most sediment transport models make a number of assumptions which may not be appropriate for mixed sand and gravel beaches: they characterise beach sediment by one parameter, usually $D_{50}$, and assume that sediment properties do not vary cross-shore, longshore, vertically or through time. They assume an infinite supply of uniform sediment which is available for transport, and assume an impermeable surface, ignoring infiltration and exfiltration. They assume an aquifer geometry. They assume a simple threshold of motion based on the defined grain size. Most models do not allow for tidal variation. Although this reduction in complexity may be useful in the initialisation of numerical models, the problem with this approach is that it assumes that the sediment dynamics are either similar to those within an environment composed of uniform sediments or equivalent to the linear summation of results determined for individual grains within an overall distribution.

**Recharge material**

Recharge material dredged from offshore, often containing a significant amount of sand, is increasingly used to replenish mixed sand/gravel beaches. Because beach recharge materials can contain a larger proportion of fine sediment than the natural beach, sediment size distributions, sorting and hydraulic conductivity can be significantly altered, as is beach profile response and plan shape. Even when the size distributions of the natural sediment and the recharge sediment are quite similar, standard recovery techniques result in an increased proportion of sand on the upper foreshore, which is normally composed of coarse sediment. The higher amount of fine sediment leads to the development of cliffing around the high water mark, which results in enhanced loss of recharge material due to undercutting by wave action.

## HYDRAULIC CONDUCTIVITY AND CLIFFING ANALYSIS

The problem of cliffing of mixed sand-gravel beaches has been suspected to do with the bimodal nature of the sediment mix. The recent works of Mason (1997) and Lopez de San Román-Blanco (2003) provided clear evidence that the pore space and the hydraulic conductivity of a bimodal sand-gravel mix are closely related to the percentage of sand of the mix. Mason (1997) showed that as the sand content increases, the hydraulic conductivity of the sand-gravel mixture reduces very quickly and reaches a value that approximates that of pure sand at 30~40%. Lopez de San Román-Blanco (2003) further showed that the porosity of a bimodal sediment mix reduces to a minimum as the sand percentage increases and then increases with further increase in sand. On discussing the results of Mason (1997) and her own, Lopez de San Román-Blanco hypothesised that as the sand content increases from 0 to 100%, the sediment mix goes through three different states: the gravel pore space being "under-filled", "fully-filled" and "over-filled". The "under-filled" mix is where the sand content is not enough to fill the pore space between the gravel particles while the "over-filled" mix is where there is more sand than that required to fill up the gravel pore space. The "fully-filled" stage is a transitional zone between the under-filled and over-filled stages. Theoretically speaking, the "fully-filled" stage is a point at which the bulk volume of the sand is equal to that of the gravel pore space. For clarity, we call this point the critical point.

To explore the possible underlying relationship between the cliff formation and bimodality of mixed sediment, we first took a theoretical approach, examining the hydraulic conductivity as a function of the sand percentage. This was then followed by a series of cliffing tests in the laboratory conditions. The study is based on a simplified model where the sediment mix contains sand of a single size and gravel also of a single size. The notations employed in the text are $\rho_s$ for the density of pure gravel/sand; $n_g$ ($n_s$) for the porosity of pure gravel (sand); $k_g$ ($k_s$) for the hydraulic conductivity of pure gravel (sand); and $\lambda$ for the percentage of sand by weight. The porosity n, hydraulic conductivity k and bulk density $\rho_{bulk}$ of a mixed sediment may be estimated by the following equations:

$$\begin{cases} n = \dfrac{n_g - \lambda}{1 - \lambda} & (\lambda \le \lambda_c) \\ n = \dfrac{\lambda n_s}{1 - n_s(1 - \lambda)} & (\lambda \ge \lambda_c) \end{cases} \quad (1)$$

$$\begin{cases} k = k_g(1 - \xi)^2 + k_s n_g \xi & (\lambda \le \lambda_c) \\ k = \dfrac{k_s \lambda}{\lambda + (1 - n_s)(1 - \lambda)} & (\lambda \ge \lambda_c) \\ \xi = \dfrac{(1 - n_g)\lambda}{n_g (1 - n_s)(1 - \lambda)} \end{cases} \quad (2)$$

$$\begin{cases} \rho_{bulk} = \dfrac{\rho_s (1 - n_g)}{1 - \lambda} & (\lambda \le \lambda_c) \\ \rho_{bulk} = \dfrac{\rho_s (1 - n_s)}{1 - n_s(1 - \lambda)} & (\lambda \ge \lambda_c) \end{cases} \quad (3)$$

$\lambda_c$ refers to the critical sand percentage and is given by

$$\lambda_c = \frac{n_g(1 - n_s)}{1 - n_g n_s} \quad (4)$$

The corresponding critical porosity, hydraulic conductivity and bulk density of the sand-gravel mix are given by

$$\begin{cases} n_c = n_g n_s \\ k_c = k_s n_g \\ \rho_{bulk,c} = \rho_s(1 - n_s n_g) \end{cases} \quad (5)$$

The equations above were successfully validated against the experimental results of Mason (1997) and Lopez de San Román-Blanco (2003), and additional test results carried out in the present study. The comparison between the analytical predictions and laboratory data are shown in Figures 2 to 5. The following observations may be made based on the theory and experimental data:

- The hydraulic conductivity of the sand-gravel mix reduces rapidly with increased sand percentage, but it reaches a minimum at the critical sand percentage. As can be expected, the porosity of the mix is also at a minimum at this point while the bulk density is at a maximum. High percolation flow allowed in a gravel beach is a distinct advantage over a sand beach in terms of dissipation of wave energy. This advantage disappears when the sand percentage of a mixed beach increases to beyond approximately 20%. The beach is possibly most inefficient when the sand percentage is at a critical value.

- The occurrence of cliffing also seems to be closely related to the sand percentage. To provide evidence for this, we carried out a series of simple "sand castle" tests using sand-gravel mixes of a range of sand percentages, as demonstrated by Figures 6 & 7. For sand percentages below that of the critical value, the "sand castles" all collapsed upon removing the plastic container used to form the "sand castle". At and above the critical sand percentage, the "sand castles" all stood up but their load bearing capacity varied with the sand percentage, as shown in Table 1. The load bearing capacity of the "sand castle" at the critical sand percentage appears similar to or higher that at higher sand percentages. The implication is that cliffing is most likely to occur when the sand percentage is equal to or greater than that of the critical value.
- Tests also showed that the loading capacity of the "sand castles" significantly increased when an increased compaction was introduced. It can be shown that compaction leads to reduced hydraulic conductivity and increased bulk density of the sediment mix, as demonstrated by Figures 8 & 9. Compaction also results in a smaller value of the critical sand percentage. As compaction is inevitable in any beach recharge operations, cliffing becomes more likely or more severe. In practice, a sand percentage of 30% should not be exceeded if severe cliffing is to be avoided.

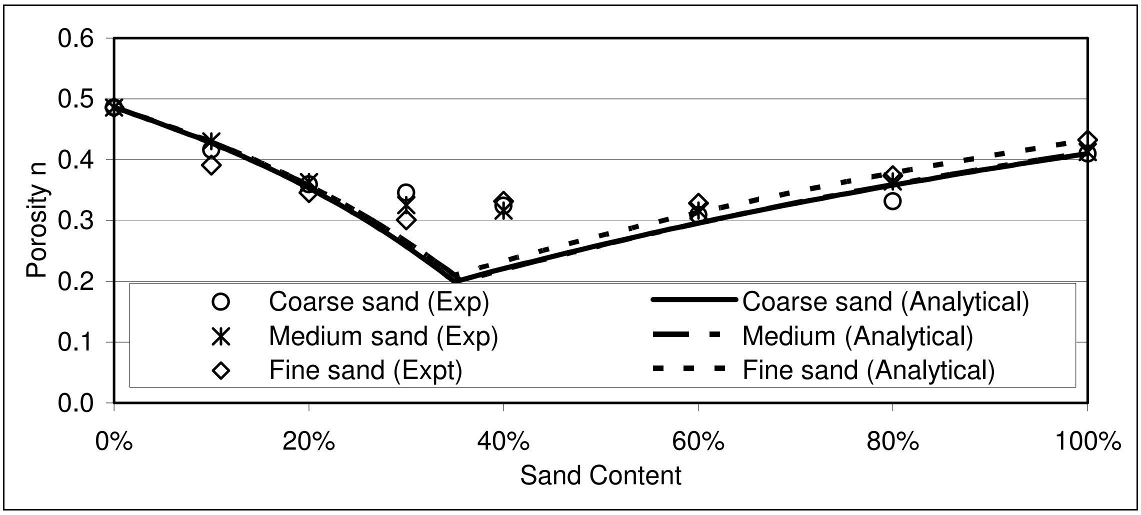


**Figure 2 Comparison between analytical prediction and measured porosity (present study)**

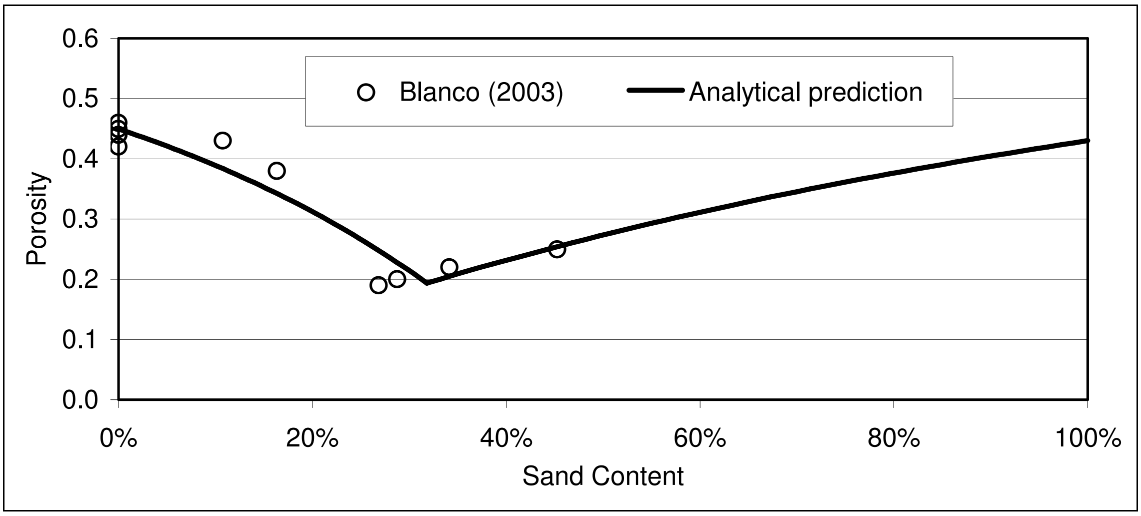


**Figure 3 Comparison between analytical prediction and measured porosity of Román-Blanco (2003)**

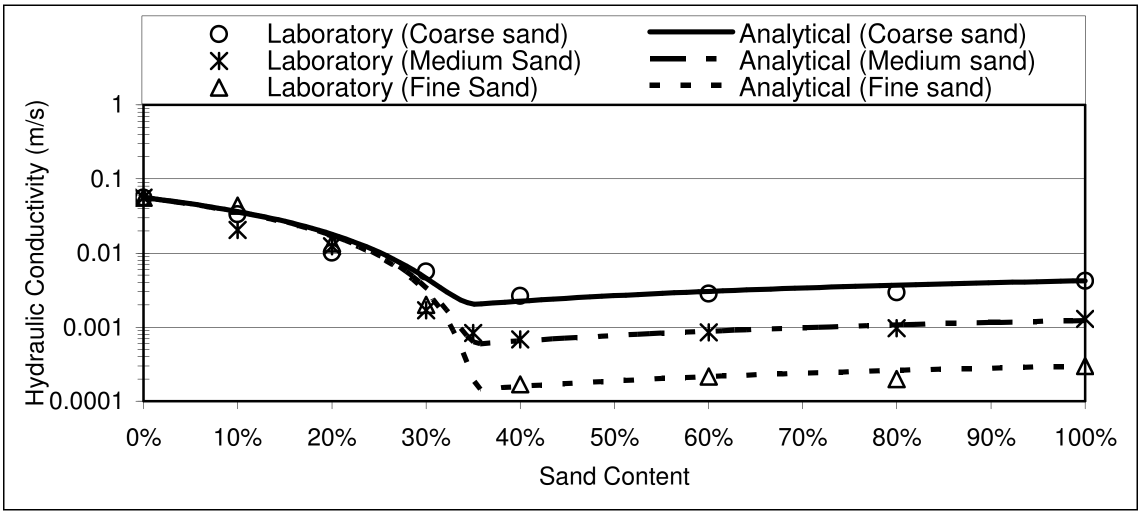


**Figure 4 Comparison between analytical prediction and measured permeability (present study)**

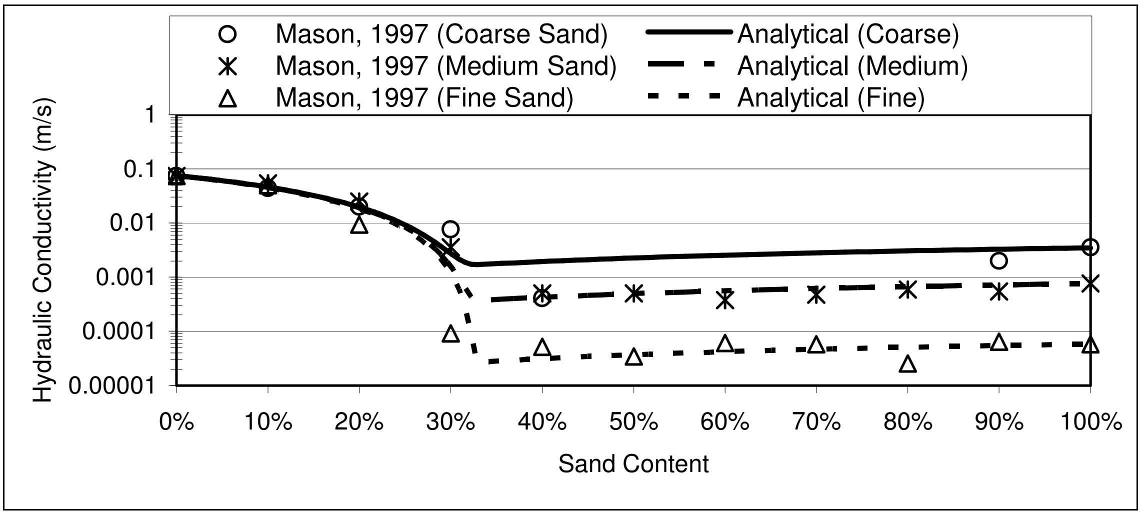


**Figure 5 Comparison between analytical prediction & measured permeability of Mason (1997)**

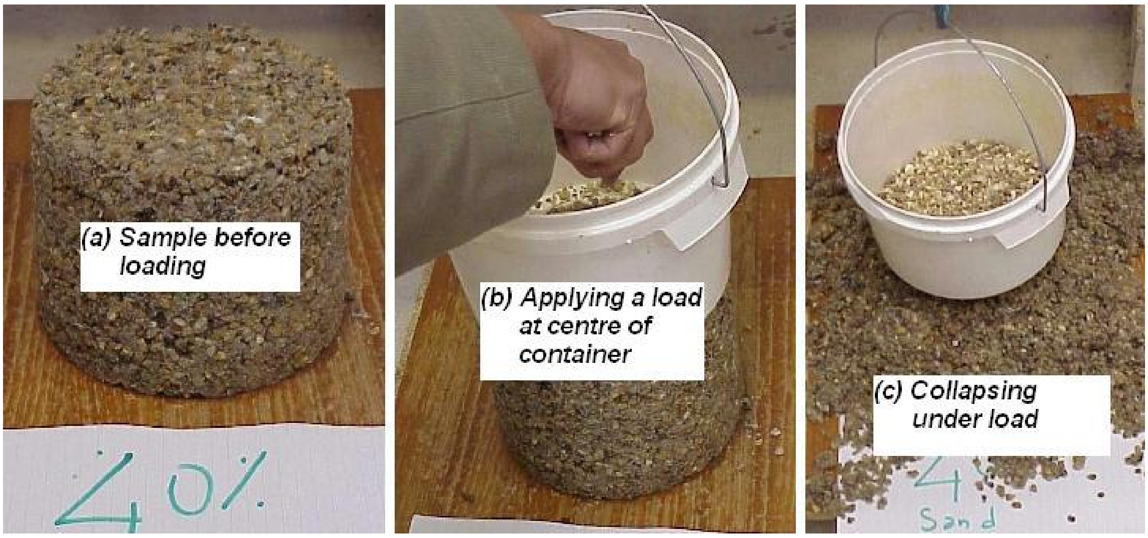


**Figure 6 Different stages of "sand castle" test (λ = 40%)**

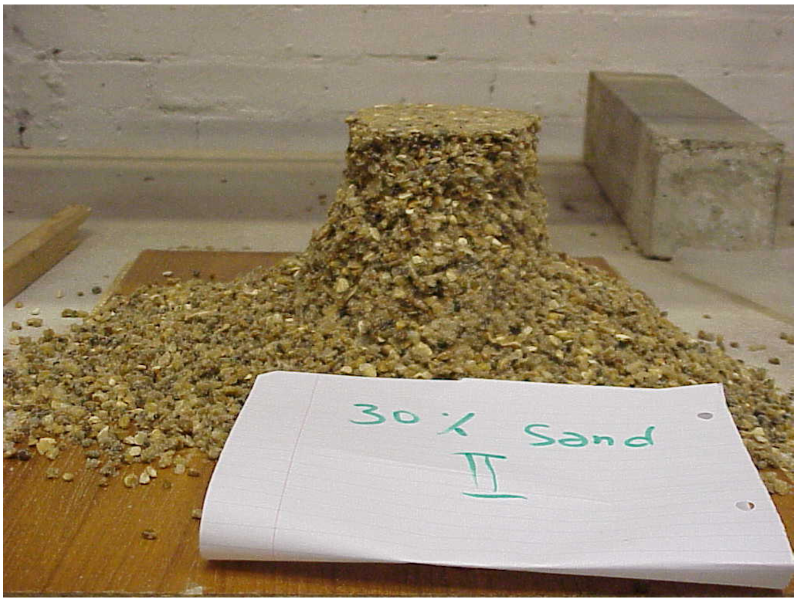


**Figure 7 Collapsed “sand castle” without load (λ = 30%)**

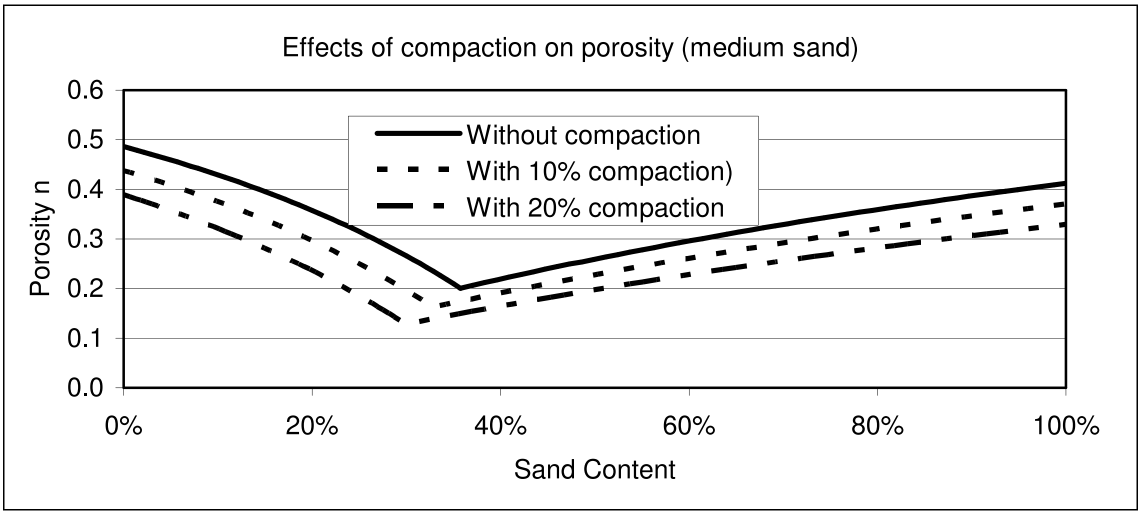


**Figure 8 Effects of compaction on porosity of mixed sediment**

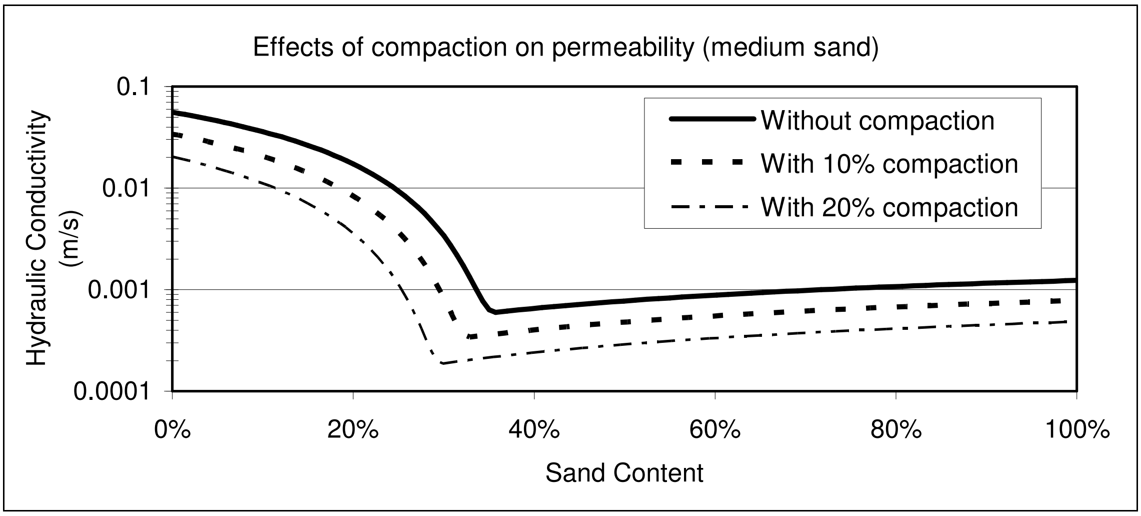


**Figure 9 Effects of compaction on permeability of mixed sediment**

**Table 1 Collapsing load of "sand castles"**

| Sand percentage | Test 1 Load (N) | Test 2 Load (N) | Mean (N) |
|---|---|---|---|
| 36% | 7.2 | 10.8 | 9.0 |
| 40% | 5.9 | 7.3 | 6.6 |
| 50% | 5.4 | 9.6 | 7.5 |
| 100% | 7.7 | 8.0 | 7.8 |

## PERMEABILITY VERSUS BEACH PERFORMANCE – LABORATORY-BASED ASSESSMENT

The influence of the permeability or hydraulic conductivity on the performance of a mixed beach may be best assessed by means of specially designed laboratory experiments. Although the nature of the current project did not allow for new experiments to be carried out, we were able to investigate the performance issues of mixed beaches by re-examining some existing experimental data collected at the University of Brighton (Trim 2003). The experiments of Trim were designed to look at beach modelling issues and the setup was such that additional analysis would provide a good indication of the performance of a mixed beach against a gravel beach.

The experimental data were obtained using two parallel beach models at a scale of 1:30. One model reflected a single sized gravel beach and the other a mixed sand-gravel beach. The two model beaches had an identical median sediment size ($D_{50}$), with the sediment grading shown in Figure 10. Both beaches had an initial slope of 1:7. Identical wave conditions were applied to the two models. The particular setup of the experiments meant that any behavioural differences in the beach evolution may be broadly linked to the differences in the permeability of the beaches.

At the 1:30 scale, the mixed beach model was expected to represent a prototype sand-gravel beach containing approximately 10% sand. The equivalent prototype $D_{50}$ is about 15 mm and the water depth at the toe is 4.8 m. The beach surface evolution was monitored under a range of wave conditions (Table 2) for a duration of 30 minutes (~3 hours under prototype conditions). A number of observations may be made with respect to the profile measurement:

- In terms of the profile changes, the gravel model beach and the mixed beach model showed similarities as well as differences. Both models showed rapid changes within the first few minutes of the test and a pseudo-steady state was attained in 10 minutes. The general trend of profile evolution (the direction of the sediment movement as onshore/offshore transport) was similar between the two model beaches. The primary difference between the two beaches was in the quantity of sediment movement. Where onshore transport took place, the mixed beach experienced less movement of material, as demonstrated by Figures 11 & 12. In the case of offshore transport, the profiles of the mixed beach showed greater losses of material from the beach crest. This may be seen from Figures 13 &14.
- The above phenomenon may be closely related to the hydraulic conductivity of the beach. The coarse grained beach model represents a gravel beach while the mixed beach model represents a mixed sand-gravel beach. The percolation flow in the gravel beach is much greater than that in the mixed beach due to the difference in the permeability (hydraulic conductivity). In the cases where the wave energy and period are such that onshore transport takes place, the wave breaking brings the sediment particles into temporary suspension and at the same time creates an uprush that takes the sediment up the beach surface. The

subsequent backwash brings some of the sediment back down. The net sediment deposition is the difference between the sediment taken up the slope during the uprush and that taken down the slope by the backwash. The gravel beach allows much greater percolation flow into the beach, thus reducing the uprush but more significantly the backwash. As a result, greater onshore transport takes place on a gravel beach than on a mixed beach even though the wave conditions are identical.

- In storm conditions, the backwash carries sufficient energy to move more sediment than that by the uprush, due in part to the slope advantage of the backwash and in part to a more saturated beach head. In comparison, a mixed beach is more saturated due to smaller percolation flow within the beach, which may be identified in terms of an increased groundwater level in the beach crest. This means an increased backwash on the mixed beach compared to a gravel beach. The result is that, under the same wave conditions, a mixed beach loses more material than a gravel beach.
- The first implication from the experiments and above analysis is that a mixed sand-gravel beach is unlikely to perform as well as a pure gravel beach as a result of a reduced onshore transport and an increased offshore transport. The second implication is that the hydraulic conductivity of the sediment bed is of great significance in influencing the sediment transport processes on the beach.
- It has been shown that the reduction in the hydraulic conductivity is approximately proportionate to the sand percentage. Reducing the sand fraction in the recharged material seems to hold the key to improved beach performance. The problem is that the material resources are relatively limited and separating gravel from the sand incurs a significant additional cost. Given such constraints, the question becomes whether the existing beach recharge techniques can be improved, or new techniques tried so that the upper section of the beach receives relatively coarse material while the lower section is left with the finer sediment material.

**Table 2 Experimental wave conditions**

| EXPERIMENTAL CONDITIONS | | | |
|---|---|---|---|
| **Model Frequency** | **Model Wave Height** | **1 in 30 Scale** | |
| | | **Prototype Frequency** | **Prototype Wave Height** |
| **Monochromatic Wave Conditions** | | | |
| **0.53Hz** | 0.02m (A), 0.04m (B) | 0.10Hz | 0.6m, 1.2m |
| **1.05Hz** | 0.02m (C), 0.04m (D), 0.06m (E) | 0.19Hz | 0.6m, 1.2m, 1.8m |
| **1.58Hz** | 0.02m (F), 0.04m (G), 0.06m (H) | 0.29Hz | 0.6m, 1.2m, 1.8m |
| **Random Wave Conditions** | | | |
| **0.53Hz** | 0.052m (I), 0.084m (J) | 0.10Hz | 1.6m, 2.5m |
| **1.05Hz** | 0.033m (K), 0.053m (L), 0.069m (M) | 0.19Hz | 1.0m, 1.6m, 2.1m |
| **1.58Hz** | 0.025m (N), 0.04m (O), 0.052m (P) | 0.29Hz | 0.8m, 1.2m, 1.6m |

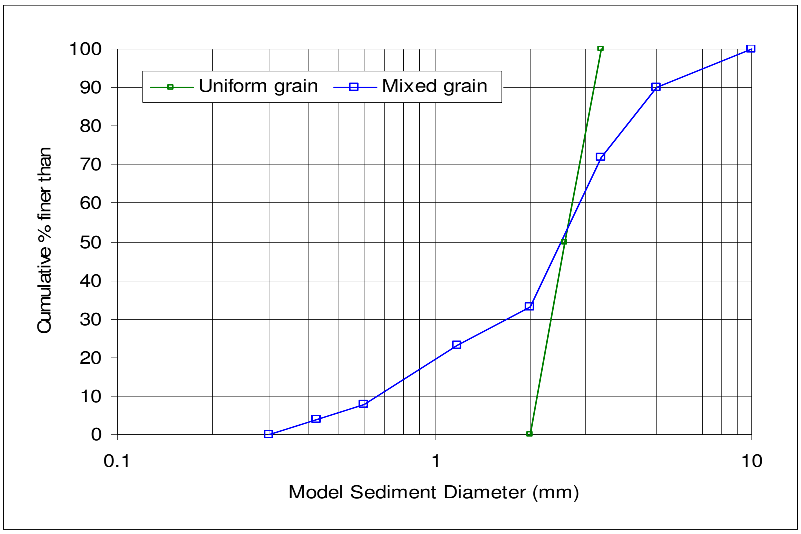


**Figure 10 Sediment characteristics of beach models**

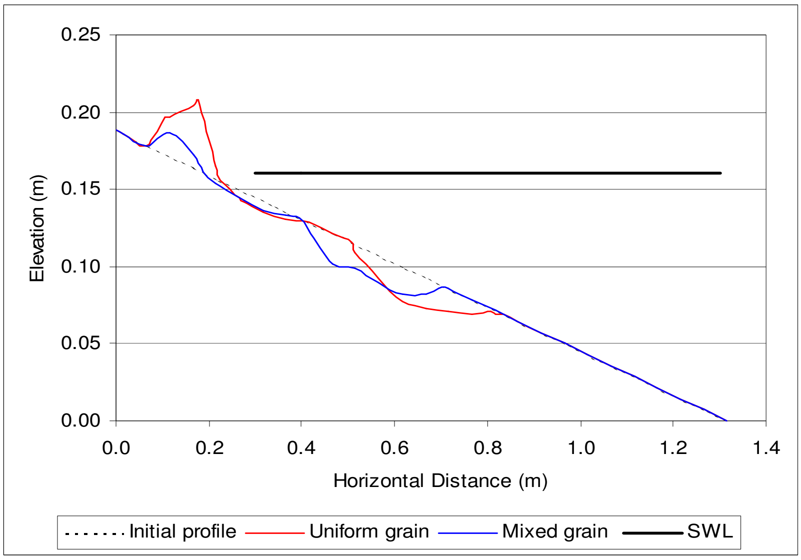


**Figure 11 Comparison of uniform grain and mixed grain beach profiles (Monochromatic wave condition: f=0.53Hz, H = 0.02m)**

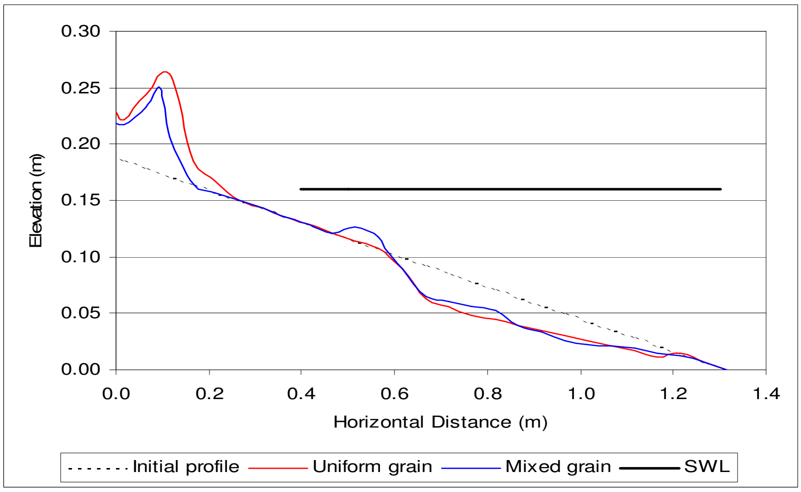


**Figure 12 Comparison of uniform grain and mixed grain beach profiles (Random wave condition: $f_s$=0.53Hz, $H_s$ = 0.052m)**

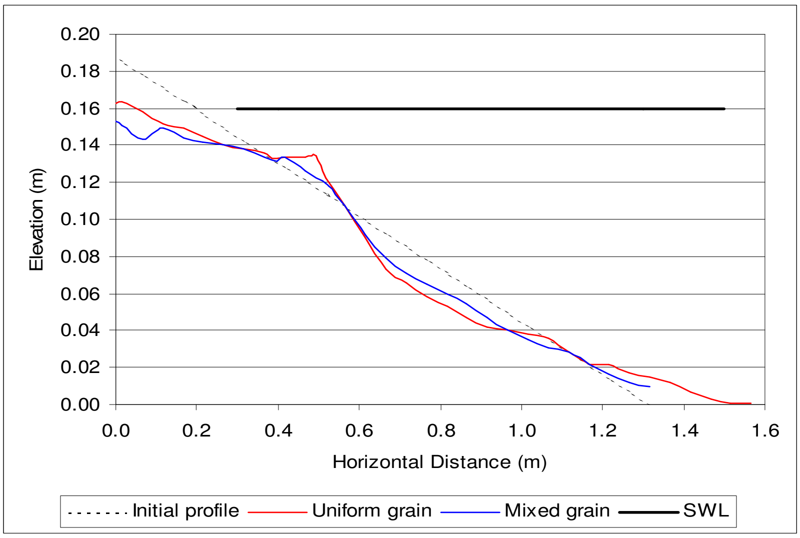


**Figure 13 Comparison of uniform grain and mixed grain beach profiles (Monochromatic wave condition: f=1.05Hz, H = 0.06m)**

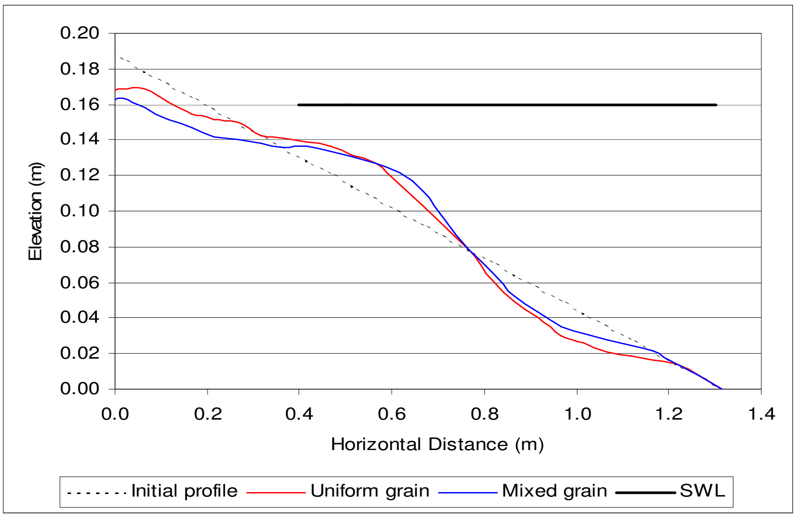


**Figure 14 Comparison of uniform grain and mixed grain beach profiles (Random wave condition: $f_s$=0.53Hz, $H_s$ = 0.084m)**

## LABORATORY TESTS AND NUMERICAL MODELLING OF FINE AND COARSE SAND BEACHES

BeachWin (Li et al. 2002) is a numerical model that simulates interacting wave motion, beach groundwater flow and sediment transport in the nearshore zone (swash zone and part of the surf zone). Making use of this numerical model, the effects of the groundwater flow on the evolution of a coarse grained and a fine-grained beach are examined with the support of experimental results obtained in collaboration with the University of Queensland, Australia. The experiments were carried out in a wave flume 27.3 m long, 1.4 m wide and 0.8 m deep. A set of 20 damped manometer tappings provided time-averaged mean piezometric head levels in the cross-shore direction from offshore to the back of the beach. Two sets of experiments were carried out, with coarse sand ($d_{50}$=0.84 mm) and fine sand ($d_{50}$=0.197 mm). In all experiments, the initial beach profile was planar, with a slope of approximately 1:7.6. For each sediment size, experiments were run with regular waves at three wave frequencies (0.4, 0.6 and 1 Hz), three wave heights (0.05 m, 0.1 m and 0.15 m), and three groundwater levels in the beach (0.05 m above SWL, 0.05 m below SWL and equal to SWL), in order to simulate high tide, low tide and mid-tide conditions. In terms of flow through the beach, the coarse sand beach is comparable to a gravel beach at full scale (Table 3). The wave parameters represented both storm and swell conditions.

On the coarse sand beach, with a lower watertable, a higher berm was formed in accretionary conditions (Figure 15). Under erosional conditions, slightly less erosion was observed on the upper beach, although little change was observed below mean sea level. A higher groundwater level promoted offshore sediment transport, with the associated formation of a smaller berm for swell profiles (Figure 17) and increased beachface erosion in storm conditions. In general, however, onshore sediment transport was enhanced when the groundwater level was lowered under both accretionary and erosive conditions. For swell profiles under the same wave conditions, a berm developed on the coarse sand beach, whereas the fine sand beach showed net offshore transport. This trend was most pronounced for lowered groundwater levels. In contrast, the back beach groundwater level had less effect on beach profile evolution under storm conditions. This suggests that artificially lowering groundwater levels would not help much in the control of storm erosion, but could promote accretion on permeable beaches. Beach profile evolution had little effect on measured or modelled piezometric heads, which are primarily governed by the back beach head level and the wave run-up limit. Groundwater levels were always higher on the coarse sand beach than on the fine sand beach, due to greater infiltration rates. The coarse sand beach was almost fully saturated for raised groundwater levels, but this was not the case for the fine sand beach. Predictions of piezometric heads in the beach show good agreement with measurements, but overestimate head levels offshore. This appears to be due to the model’s over-estimation of set-up, which is probably related to the energy dissipation routine in the model. Model predictions are better for the coarse sand beach than for the fine sand beach (Figures 18 and 19). The model tends to underestimate groundwater levels for longer period waves and overestimate them for shorter period waves.

**Table 3 Model and prototype parameters**

| LAB PARAMETER | PROTOTYPE (STORM) | PROTOTYPE (SWELL) |
|---|---|---|
| **Period (sec)** | **scaling 1:√10** | **scaling 1:√25** |
| 2.5 | 7.9 | 12.5 |
| 1.67 | 5.28 | 8.35 |
| 1 | 3.16 | 5 |
| **Wave height (m)** | **Scaling 1:10** | **scaling 1:25** |
| 0.05 | 0.5 | 1.25 |
| 0.1 | 1 | 3.75 |
| 1 | 1.5 | 3.75 |
| **$D_{50}$ (mm)** | **scaling 1:4.2** | **scaling 1:8.4** |
| 0.835 | 3.51 | 7.01 |
| 0.197 | 0.83 | 1.65 |

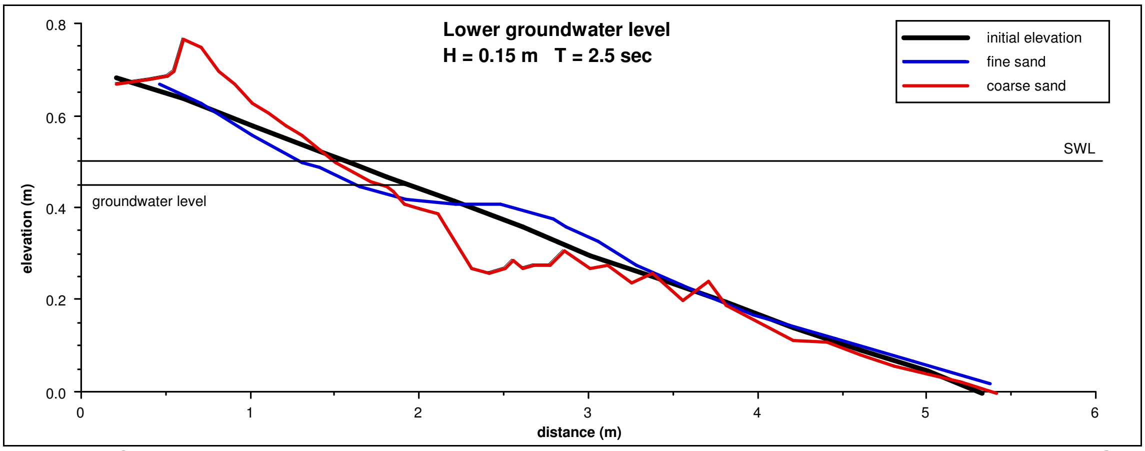


**Figure 15 Comparison of fine and coarse sand profiles, inland groundwater level below SWL**

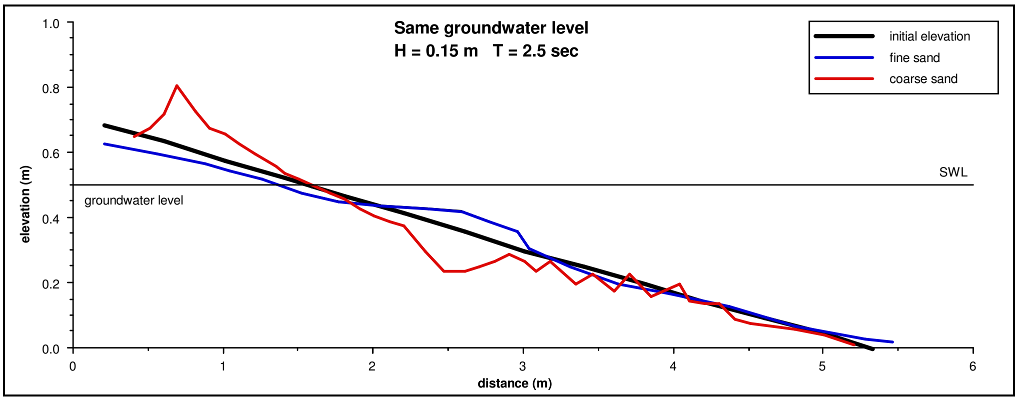


**Figure 16 Comparison of fine and coarse sand profiles, inland groundwater level the same as SWL**

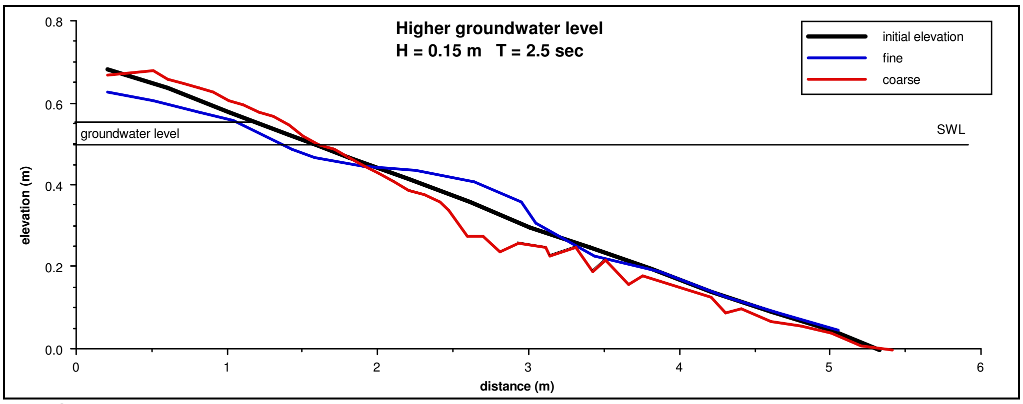


**Figure 17 Comparison of fine and coarse sand profiles, inland groundwater level above SWL**

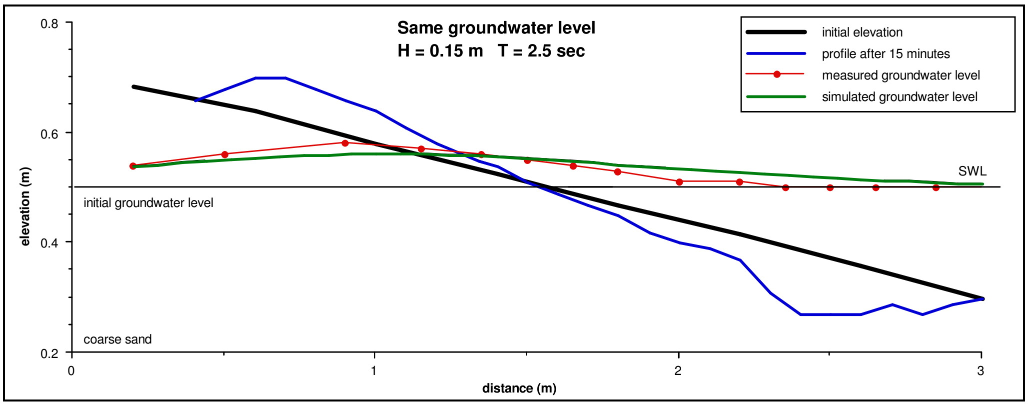


**Figure 18 Comparison of measured and modelled groundwater levels on the coarse sand beach, inland groundwater level the same as SWL**

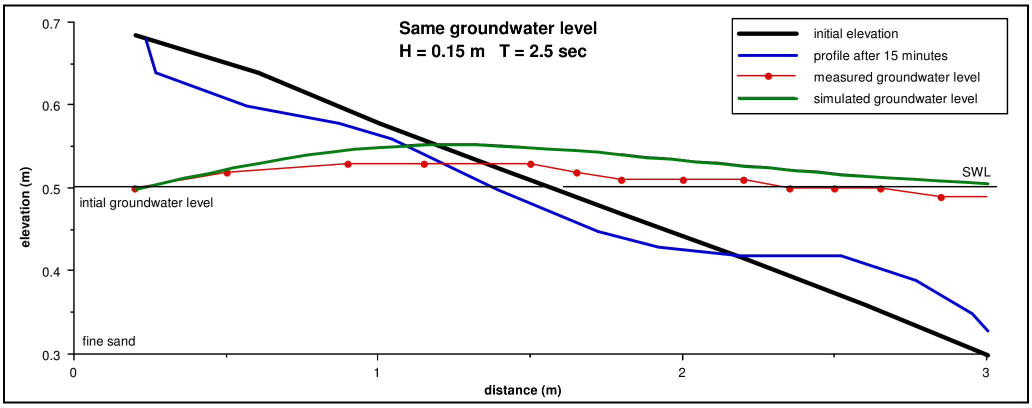


**Figure 19 Comparison of measured and modelled groundwater levels on the fine sand beach, inland groundwater level the same as SWL**

## CASE STUDIES OF MIXED BEACH RECHARGE SCHEME

The following is a summary of the case studies with respect to Pevensey Bay, Eastoke Hayling Island and Tankerton Bay.

A questionnaire was sent out in July 2005 to selected coastal authorities to gather information on mixed beach locations, characteristics, and beach recharge methodologies. From the questionnaire responses and subsequent Steering Group discussions, four beach recharge schemes were chosen for the case studies: Pevensey Bay, Kingsdown, Eastoke Hayling Island and Tankerton Bay. As the cases studies progressed, the Kingsdown site was dropped as a result of relatively limited data. The locations of the final three sites are shown in Figure 20.

The case study work focussed on the performance of the recharge schemes (in relation to beach profile and volume response to common and storm events, and related standard of protection), the methods used to manage sediment transport, and the related costs of these operations. The main findings of the case studies are as follows:

- The case studies highlighted two of the most problematic performance issues. The first is loss of crest height and width, generally due to the transport of sediment from the upper beach to the lower beach, and the second is cliffing, particularly in newly recharged material. It has previously been noted that along the UK coastline mixed beaches typically have a sand fraction of 20 to 30% of the total beach volume. The schemes assessed in this study are no exception to this observation. The Tankerton site included an experimental bay with a sand percentage of ~40% and the Hayling Island frontage also contained a bay with similarly high sand percentage. The most severe of the observed cliffing was associated with these bays with high sand fractions. This is significant, as parallel theoretical and laboratory investigations carried out in this project have indicated that the overall performance of mixed beaches is highly dependent on the sand fraction, in particular when it is in the region of 30 to 40%. Within this range the hydraulic conductivity (and permeability) of the sediment matrix is at a minimum, and it has been observed that this results in a tendency for cliffing to occur.
- The mechanism of cliffing is complicated. The high sand fraction is clearly a major factor. Detailed records of beach profiles and wave climate at Hayling Island suggest two other important factors. The first is the presence of sustained swell waves of sufficient wave energy. The two severe cases of cliffing (where cliffs of ~1.7m height were formed) were both proceeded by swell waves approaching 2m with dominant periods of 15s. The second factor is the presence of a steep slope in the upper section of the beach which significantly

exceeds the “natural” slope corresponding to sediment grading of the beach. Laboratory studies (Trim et al. 2002) suggest that irrespective of the initial slope, a mixed beach tended to settle down to a mean slope of 1:8.5 to 1:9.5. This is in line with the beach slopes found in the post-storm surveys along the Eastoke frontage.

- A slope of around 1:7 is a commonly used design slope. The large loss of the beach crest material in a storm event may be attributed to the very fact that such design slopes are not naturally sustainable. Given a limited supply of material, the high design slope is necessary to form a beach head of sufficient width. This superficially wide beach crest may give a false impression of security in the event of a storm, as it can take just a fraction of a tidal cycle for a whole beach head to be destroyed. Laboratory tests indicate that the most significant material movement under storm conditions takes place in the first 30 minutes to an hour. This means that the protection provided by the width of the beach head can vanish in a matter of an hour. The current design practice needs to be further investigated in future studies by way of laboratory tests and experimenting in prototype conditions.
- The Tankerton experiment has the potential of providing a better insight of groundwater behaviour of newly recharged beaches in contrast to a fully developed beach. It is also clear that controlling the sand percentage is a key to alleviating the problem of cliffing. Placing a gravel top layer on top of the mixed material seemed to an effective way of eliminating the cliffing problem, but the economic viability in large scale operations needs to be looked at in greater depth.
- The compaction due to heavy plant operations on the beach also has a negative consequence in terms of the beach performance and cliffing. Heavy compaction means a smaller threshold sand percentage at which severe cliffing occurs.
- In relation to spreading of the tipped recharge material, recycling operations at both Pevensey Bay and Eastoke Hayling Island have evolved to use the most appropriate sediment: particularly coarse sediment is recycled from the west to the central portion of the scheme extent at Eastoke Hayling Island, whilst at Pevensey Bay sediment is generally contained within the locality it came from by regular operations. Recycling costs are generally in the range of £1 to £2/m$^3$, with recharge costs around £20/m$^3$, and so economically there is significant benefit in ensuring recharge and native sediment is not lost from the beach. This is confirmed by frequent recycling operations at Pevensey Bay and to a lesser extent at Eastoke Hayling Island.


**Figure 20. Locations of case studies**

## AGGREGATE PRODUCTION, PLACEMENT AND MIXING METHODS

A wide range of research is currently being carried out to investigate the most effective use of sand and aggregate resource, from both land and sea sources. The following organisations have ongoing research programmes and/or data relevant to this project: the Crown Estate; Office of the Deputy Prime Minister; CIRIA; Aggregate Sustainability Levy Fund (ASLF); British Marine Aggregate Producers Association (BMAPA); British Geological Survey (BGS); MIRO; MIST; SAMP; and AggRegain. The current study review draws from a number of publications sourced from these organisations, and from site specific dredging information from the current case studies (Pevensey Bay, Eastoke Hayling Island and Tankerton Bay) and the main findings are as follows:

- Aggregate production for beach recharge schemes is sourced from a number of sites, either from the land or from the sea. Irrespective of the aggregate source, the availability of sand and gravel resources is always limited. Therefore there is a need to use these resources in an efficient and sustainable manner. This need is further reinforced by sound economic requirement. In direct contrast to the sustainability and economic requirements, performance issues of the beach renourishment schemes dictate high specifications for aggregates, requiring relatively well defined sediment gradings to ensure adherence to the scheme design and acceptable beach performance. This contradiction means that improved performance of recharged beaches will have to be achieved primarily by means of improved placement and mixing techniques.
- The main methods of placing dredged sand and gravel on mixed beaches include split bottom dumping, rainbowing, and direct from shallow bottom barges. It is apparent from comparison between different recharge events in the case studies that the rainbow method is a more efficient method of placing material on the beach, tending to result in losses of up to 15% rather than up to 30% for the split bottom method. However, it has been observed that the reduction in sediment loss comes mainly from increased retention of sand, which can result in increased volumes of sand being distributed throughout the cross-shore profile of the beach.
- Assessment of the costs related to the various dredging and recharge methods indicate very little dependency on placement method, with present day rates generally around £20/$m^3$. Although the different initial placement methods result in a large variation in initial losses, the scheme costs are not directly impacted as general practice now is to provide a cost for the final placed volume. However, there is an inferred cost in that recharge sediment is effectively being used with variable efficiency.
- Spreading of the recharge material after initial placement is generally carried out via heavy plant for all the case studies, resulting in a relatively well mixed layer of sediment across the cross-shore beach profile. As noted previously, this gives artificially raised levels of sand volume in the upper beach, which tends to increase cliffing and the erosion rate of the beach crest. An improved spreading technique has been trialled at Pevensey Bay since autumn 2003. The technique involves selectively moving sediment from the recharge mound so that coarser sediment is transferred to the upper beach. This is dependent on the intermediate partial separation of the tipped material by wave/tidal action when using the rainbow method. Initial results indicate that this method reduces cliffing, but further study of this technique is required.
- The use of marine dredged sand and gravel for beach replenishment is relatively minor compared to the amount used for other purposes. Currently, the amount of sand and gravel dredged is well within the permitted dredge volume. The initial aggregate resource review has indicated the existing physical resource for beach replenishment is acceptable for the near future. Land based quarries represent a significant source of sand and gravel, but qualitatively transport costs are a major factor limiting the use of sediment from this source. However, further data is required to ascertain the amount of available sediment that would be within design gradings for mixed beach replenishment schemes.

## CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The influence of permeability on the performance of shingle and mixed beaches has been examined by means of a literature review; an analytical study in conjunction with some laboratory experiments; a re-analysis of existing laboratory data; a numerical analysis of groundwater flow; and finally three case studies. Conclusions and recommendations for future studies are as follows.

- There is an ambiguity in the literature as to the definition of shingle and mixed beach. The term "shingle beach" should be avoided in favour of "gravel beach", and "mixed sand-gravel beach" should be used in place of "mixed beach".
- It is beyond any doubt that the performance of a recharged mixed sand-gravel beach is closely related to the hydraulic performance of the beach. Limited laboratory results showed a mixed sand-gravel beach is likely to suffer much greater damage than a gravel beach of the same median sediment size. It is recommended that more detailed and extensive laboratory tests be carried out so as to quantify the performance of the mixed sand-gravel beaches with respect to the sand percentage.
- The hydraulic conductivity of a sand-gravel sediment mix is predominantly controlled by the sand percentage of the sediment, as indicated by the current analytical analysis and supported by past and present laboratory test results. The work within the current project was limited to single grain-sized sand mixed with single grain-sized gravel. A more detailed laboratory study should be carried out where the hydraulic conductivity is measured using mixtures of graded sand and gravel in line with what is commonly found in practice.

- The case studies identified two problems common to all recharged mixed sand-gravel beaches. The first is the problem of cliffing and the second is severe loss of beach crest material in storm events. Both problems seem to be closely linked to the presence of a relatively large sand fraction, and also an unsustainable design beach slope. Limited laboratory data and field surveys indicate that a mixed sand-gravel beach has a "natural" slope of about 1:8.5~1:9.5. It is recommended that an extended laboratory programme should be carried out to examine the most appropriate design slope. There should be a parallel programme that surveys newly recharged beaches in sufficient frequency and detail.
- For economic reasons and sustainable development, the efficiency of aggregate production has to take precedence over the quality of its production. This means that a greater emphasis has to be placed on the improvement of placement and mixing techniques of the aggregate at the point of delivery. The ongoing field experiment at the Tankerton site showed one possible approach, by combining a gravel top layer with an underlayer of normal mixed sand-gravel material. The Hayling Island frontage also experimented with the beach head being constructed with recycled gravel. Additionally, at Pevensey Bay a new sediment spreading technique has been tried out. It is recommended that such field experiments should continue, but additional support should be given so that continuous monitoring can be carried. Well planned post-project monitoring is crucial in achieving a full understanding of the sediment processes and the advantages and disadvantages of a particular method.
- Detailed recommendations for future action are given in Table 4 in terms of the types of study and relevant groups of interest. In addition, different orders of priorities are also suggested.

**Table 4 Matrix of recommendations**

| Type of study | Most relevant for user groups, including Defra/EA | Most relevant for researchers |
|---|---|---|
| Laboratory experiments | • permeameter measurements to investigate the effects of sediment grading and increasing sand content on the hydraulic conductivity<br>• experiments on the effect of sand fraction and other factors on cliffing<br>• experiments on the optimum design profile to reduce cliffing<br>• experiments on sediment transport and beach profile evolution using a range of sediment mixtures, with concurrent measurements of hydraulic conductivity<br>• experiments on effects of compaction | • permeameter measurements of hydraulic conductivity with a range of sediment mixtures<br>• experiments on initiation of motion using a range of sediment mixtures<br>• experiments on initiation of motion, sediment transport and beach profile evolution with infiltration/exfiltration<br>• experiments on kinetic sorting using a range of sediment mixtures<br>• experiments on reflection on mixed beaches<br>• measurements of porosity, packing, pore diameter distribution, particle shape, capillary effects |
| Field experiments | • monitor newly recharged beaches to identify times when cliffing occurs; collect sediment samples at these times to test hypotheses about causes of cliffing<br>• experiments on placement of coarse material on upper beach<br>• measurements of adjacent sites with normally placed and selectively placed recharge material<br>• continue measurements of groundwater on recharged beaches, or develop new sites for similar measurements | • detailed measurements of sediment size distributions, sand content, in-situ hydraulic conductivity, watertable elevation, moisture content, hydraulic gradients<br>• short-term tracer experiment to identify sediment transport paths on recharged beaches |
| Numerical modelling | • test predictions of existing profile evolution models against data from mixed beaches | • development of new models for mixed beaches |

| | | |
|---|---|---|
| **Recharge** | • monitor and quantify effects of recharge delivery systems and recovery techniques<br>• assess economic and technical viability of obtaining smaller volumes of coarse sediment from other sources for placing on upper beach | |
| **Other** | • ensure that regional monitoring programme receives information on recharge and recycling times and locations<br>• collect data on total amount of sand and gravel available from licensed sites<br>• collect data on future capital recharge programmes for existing schemes to define remaining life of currently licensed resource<br>• investigate the possibility of setting aside certain areas of coarse sediment for beach recharge rather than other aggregate uses | • development of standard methodology to characterise bimodal sediments |

All recommendations are in suggested order of priority within each category.
red: overall highest priority; blue: relatively low cost; purple: high priority and relatively low cost; green: long-term.

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5) Trim L. 2003. Physical modelling of shingle beaches. Unpublished PhD thesis, University of Brighton.

## References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.

## Internal Reports (distributed to the Steering Group)

1) She, K. 2005a. Hydraulic Conductivity of Bimodal Mixed Sand-Gravel Sediment, Defra Project FD1923 Internal Report No. 1.
2) She, K. 2005b, Effects of permeability on the beach performance - Laboratory tests of gravel and mixed beaches, DEFRA Project FD 1923 Internal Report No. 2.
3) Horn, D., 2005, Model tests against laboratory/field data, DEFRA Project FD 1923 Internal Report No. 3
4) She, K., Canning P. and Horn D. 2006, Case Studies and Aggregate Review, DEFRA Project FD 1923 Internal Report No. 4.
5) Horn, D. and She, K, 2006, Literature Review, DEFRA Project FD 1923 Internal Report No. 5.

## Newsletter

1) She K., 2006, Influence of permeability on the performance of mixed sand gravel beaches, Defra Newsletter

## Papers

1) She K., Horn D. and Canning P. 2006, Recharge of mixed sand and gravel beaches, ICCE2006, San Diego, Sept 2006.
2) She K., Horn D. and Canning P. 2006, Porosity and Hydraulic Conductivity of Mixed Sand-Gravel Sediment, Submitted to ASCE Journal of Waterway, Port, Ocean and Coastal Engineering
3) She K., Trim L., Horn D. and Canning P. 2006, Effects of permeability on the performance of mixed sand-gravel beaches, Coastal Sediments 2007
4) Horn, D.P., She, K.M. and Canning, P. Dynamics of mixed sand and gravel beaches. To be submitted to Marine Geology.
5) Canning, P., She, KM. and Horn, D.P. Recharge of mixed sand and gravel beaches. To be submitted to Coastal Engineering.