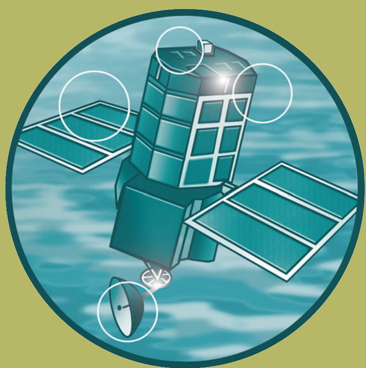
Joint Defra/EA Flood and Coastal Erosion
Risk Management R&D Programme

Influence of permeability on the performance of shingle and mixed beaches

R&D Technical Report FD1923/TR



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Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Influence of permeability on the performance of shingle and mixed beaches

Research Scoping Study

R&D Technical Report FD1923/TR

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Statement of use

This document provides information for the Defra and Environment Agency Staff about the influence of permeability on the performance of gravel and mixed sand-gravel beaches and constitutes an R&D output from the Joint Defra / Environment Agency Flood and Coastal Defence R&D programme. This report describes work commissioned by Defra under Project FD1923 Influence of Permeability on the Performance of Shingle and Mixed Beaches, within the Fluvial, Estuarine, and Coastal Processes Theme.

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Executive Summary

Many of the beaches on the UK coast that constitute the main defence against erosion and flooding are composed of highly permeable sediments, usually a mixture of sand and gravel. Recharge material dredged from offshore is increasingly used to replenish these mixed sand-gravel beaches. Because beach recharge materials may 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. Even when the size distributions of the natural sediment and the recharge sediment are quite similar, the standard recovery technique produces 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. In addition, such cliffs can be extremely hazardous due to their natural instability and for public safety may require removal at the first opportunity.

This study aims to address issues such as cliffing, the influence of permeability on the performance of recharged beaches, 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 examine possible methodology by which sediment properties on mixed sand-gravel beaches can be characterised;
- 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 sand-gravel 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.

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.

The literature review covers a wide range of topics associated with gravel and mixed sand-gravel beaches. 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) developing methodology 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

No standard method is yet available for characterising the sediments of a mixed sand-gravel beach. A primary difficulty is that mixed sand-gravel 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. However, research indicates 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 sand-gravel beaches. There is also an indication that sediment transport is affected by the relative proportions of sand and gravel, and that adding sand to mixed sediments can increase gravel transport as well as the total transport rate.

A re-analysis of some existing laboratory data was undertaken to assess performance of mixed sand-gravel beaches in contrast to that of gravel beaches. The experiments were carried out using a model gravel beach and a model mixed sand-gravel beach, both being subjected to a range of identical wave conditions. The comparison shows 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 sand-gravel 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 presence of sand in a mixed sediment has been known to affect the porosity and hydraulic conductivity of the sediment. In this study, a theoretical approach was taken using a bimodal sediment model. The constituent sand and gravel each has a known grain size, porosity and hydraulic conductivity. The analytical work led to some simple equations relating the porosity, hydraulic conductivity and bulk density of the mixed sediment to the percentage of sand. These equations were successfully validated by a series of specially designed laboratory experiments. The hydraulic conductivity of the mixed sediment is shown to be greatly influenced by the presence of sand. As the sand percentage increases, the hydraulic conductivity of the sediment mix reduces rapidly until the sand fraction reaches about 30~40%, beyond which the hydraulic conductivity remains close to but below that of pure sand. The minimum hydraulic conductivity occurs at a sand percentage in the region of 30~40%, and has a value of approximately 55% less than that of pure sand. The sand percentage corresponding to the minimum hydraulic conductivity is of critical significance and is referred to as the critical point. Additional loading experiments using "sand castle" models showed that cliffing would occur when the sand percentage exceeds the critical value, and that the load bearing capacity appeared to be greater than at higher sand percentages. The critical point thus represents the worst scenario in terms of the likelihood of cliffing.

The theoretical analysis and laboratory tests also showed that compaction of the sediment due to heavy plant operations on the beach can greatly reduce the hydraulic conductivity and lower the critical sand percentage, thus enhancing the likelihood of 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 a critical value of 30~40%. It is 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 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 beach face increases with increasing hydraulic conductivity. There is a clear need for improved numerical models specifically designed to deal with mixed sand-gravel 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 operation and the widespread problem of cliffing. At the Pevensey 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 data indicate 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 the three sites indicated that reducing the sand percentage in the upper beach had the positive effect of alleviating the cliffing problem. Reduction of the sand percentage in the upper beach or beach crest may be achieved in two ways: improved recovery technique at the point of delivery, and managed use of the sediment resources. The modified rainbowing technique experimented with at Pevensey is an example of the former, while the latter needs additional regulations by the government.

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1. Introduction

1.1 Background

Although interest in gravel and mixed sand-gravel beaches has increased in recent years, processes on coarse-grained beaches are less well understood than on sand beaches. Most sediment transport models concentrate on sand-sized sediment and surf zone processes and little field data are available to indicate the temporal and spatial variability of gravel and mixed beaches.

The sediment processes on gravel and mixed sand-gravel beaches show two distinct zones of activities, the surf zone and the swash zone. In the surf zone, the sediment particles are under the influence of the wave motion and turbulence created by wave breaking. The sediment movement is in the form of bedload and suspended load. The swash zone on steep coarse-grained beaches is characterised by a violent breaking wave impact directly on the sediment particles followed by uprush and backwash. The beach in the swash zone is partially saturated and the sediment movement is primarily bedload and/or sheet flow. Sediment transport in the swash zone is likely to be more significant on gravel beaches than on sand beaches (Van Wellen et al. 2000).

The high percolation flow allowed within the sediment media makes a gravel beach an extremely efficient system for absorbing the incident wave energy. It forms an ideal system of coastal defence against storm attacks. In practice, pure gravel beaches are rare. In cases of beach renourishment schemes, the recharged material inevitably contains a varying amount of sand. At low sand percentage, the mixed sand-gravel beach may be expected to function like a gravel beach. As the sand fraction increases, the beach permeability is likely to reduce significantly and hydraulic performance of the beach may be greatly impaired. The question is then how the presence of sand affects the performance of a mixed sand-gravel beach due to the reduced permeability of the sediment media.

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 1.1). These cliffs can be extremely hazardous due to their natural instability and for health and safety of the public may require removal at the first opportunity. The question is what causes cliffing and how the problem may be resolved or alleviated.

Figure 1.1 Cliffing photographed at Hayling Island (left) and Pevensey Bay (right)

1.2 Objectives

This study aims to address issues such as cliffing, the influence of permeability on the performance of recharged beaches, sediment resources and their management, efficiency of sediment placement techniques, and cost effectiveness of frequent and focussed recycling operations. The detailed objectives of the project are

- to produce a review of existing knowledge of the impacts of permeability on mixed and gravel beach performance;
- to investigate the cliffing problem of recharged mixed sand-gravel beaches;
- to examine possible methodology by which sediment properties on mixed sand/gravel beaches can be characterised;
- 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.

1.3 Methodology

Five distinct approaches were employed in this study:

1) **Literature review**

   This provided an overall view of the current state of knowledge and understanding in relation to gravel and mixed sand-gravel beaches.

2) **Theoretical analysis**

   This involved firstly the development of theoretical equations describing the relationship between the porosity and permeability of a mixed sediment and the sand percentage of the sediment mix. The theory was then validated by laboratory experiments. Additional series of experiments were carried out to establish the relationship between the sand percentage and cliffing problem.

3) **Re-analysis of existing gravel and mixed beach experiments**

   This examined the performance of a mixed sand-gravel model beach in contrast to a gravel beach model results. This provided an indication of the influence of permeability on the performance of the beach.

4) **Numerical modelling**

   This involved the use of a numerical model to show the influence of the groundwater level on the beach profile evolution.

5) **Case studies**

   By looking at three current/recent beach recharge programmes, significant issues in relation to beach recharge operations were identified and possible solutions proposed.

1.4 Outline of Report

The report consists of 10 chapters as follows:

1. Introduction
2. Literature review
3. Theory of bimodal mixed sand-gravel sediment
4. Performance of mixed beaches versus gravel beaches
5. Groundwater level and beach evolution
6. Case studies
7. Review of aggregate production, placement and mixing
8. Conclusions and recommendations
9. References
10. Acknowledgments

2. Literature Review

2.1 Introduction

The literature review was based on a collection of 275 publications, including journal and conference papers and government reports. The review summarises 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

- understanding the difference between coastal dynamics on mixed sand and gravel beaches and beaches dominated by relatively uniform sediment sizes (either sand or gravel)
- developing methodology to quantify and/or classify complex, spatially and temporally variable sediment characteristics effectively on mixed sand and gravel beaches
- developing methodology to parameterise the effects of bimodal sediments and mixed sand and gravel in hydrodynamic and morphodynamic models
- adapting existing numerical models to predict the processes and morphological evolution of mixed sand and gravel beaches

A detailed report of the literature review is included in Appendix 1 (Review of Mixed Sand and Gravel Beaches), and the following summarises the main findings of the review.

2.2 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.

2.3 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.
- 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.

Unidirectional flow experiments show that adding sand to mixed sediments can increase gravel transport as well as the total transport rate. The addition of sand is able to induce entrainment and transport on an armoured gravel bed where no sediment transport was occurring before the addition of the sand.

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. 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.

2.4 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.

2.5 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.

2.6 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.

2.7 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.

2.8 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.

2.9 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.

In order to reduce cliffing, recharge sediment should contain as little sand as possible, and certainly no more than 20-30%. There is some evidence to support the use of fill sediment which is coarser and more poorly sorted than the native material.

3. Theoretical Study of Mixed Sand-Gravel Sediment

3.1 Introduction

The problem of cliffing of mixed sand-gravel beaches has been suspected to be closely associated with the bi-modal nature of the sediment mix. Mason (1997) showed that as the sand fraction 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%. Román-Blanco (2003) further discussed Mason's results and also provided experimental data that showed a similar behaviour in terms of the porosity of a bi-modal sediment mix. Román-Blanco (2003) hypothesised that as the sand content increases from 0 to 100%, the sediment mix may be said to be "under-filled", "fully-filled" and "over-filled". The "under-filled" state is where the sand content is not enough to fill the pore space between the gravel particles, while the "over-filled" state is where there is more sand than that required to fill up the gravel pore space. The "fully-filled" state is a transitional zone between the under-filled and fully-filled stages. Theoretically speaking, the "fully-filled" state represents a single point at which the bulk volume of the sand is equal to that of the gravel pore space. This point is of particular importance, as will be shown later, and is referred to as the critical point.

The following presents an analytical solution linking the porosity and permeability of a sediment mix to the respective values of the constituent sand and gravel.

3.2 Porosity Analysis

Let λ be the percentage of sand content by weight. The porosity of the pure gravel aggregate is n_g and the pure sand aggregate has a value of n_s. For simplicity, we assume that both sand and gravel have the same density of ρ_s.

First consider the under-filled state. In this case, the pore space of the sediment mix is the pore space of the pure gravel minus the solid volume of the sand. Making use of this fact, we can show that the porosity of the sediment mix may be expressed as

$$n_{under\text{-}filled} = \frac{n_g - \lambda}{1 - \lambda} \tag{3.1}$$

In the case of the overfilled state, the pore space of the mixed sediment is equal to the pore space of the sand. As a result, we have an equation for the porosity of an overfilled sand-gravel mixture as follows

$$n_{over\text{-}filled} = \frac{\lambda n_s}{1 - n_s(1 - \lambda)} \tag{3.2}$$

At the critical point, $n_{under\text{-}filled} = n_{over\text{-}filled}$. The critical sand percentage and critical porosity can be thus be derived from equations (3.1) and (3.2) and these are

$$\lambda_c = \frac{n_g(1 - n_s)}{1 - n_g n_s} \tag{3.3}$$

$$n_c = n_g n_s \tag{3.4}$$

In summary, the porosity of a bi-modal mixed sand-gravel sediment may be given by

$$\begin{cases} k = k_g(1 - \xi)^2 + k_s n_g \xi & (\lambda \le \lambda_c) \\ k = \dfrac{k_s \lambda}{\lambda + (1 - n_s)(1 - \lambda)} & (\lambda \ge \lambda_c) \end{cases} \tag{3.5}$$

3.3 Hydraulic Conductivity

Let k_g and k_s be the hydraulic conductivity of pure gravel and pure sand, respectively. The derivation of the hydraulic conductivity of the mixed sand-gravel sediment makes the following assumptions:

- The flow through the sediment media is laminar and obeys Darcy's law; i.e., the flow velocity and hydraulic gradient is related to the hydraulic conductivity by

  $v = ki$

- The flow through the sediment pores may be approximated by that through parallel pipes each having a length L and an effective diameter d. The diameter d is further assumed to be proportional to the sediment size and porosity.
- The Hagen-Poiseuille equation for laminar pipe flow applies; i.e., the energy loss h is related to the seepage velocity $v_{seepage}$ by

  $$h = \frac{32\mu L v_{seepage}}{\rho g d^2} = \frac{L v_{seepage}}{C d^2} \quad \text{or} \quad i = \frac{h}{L} = \frac{v_{seepage}}{C d^2}$$

  where μ and ρ are the viscosity and density of the water, respectively, and g is the acceleration due to gravity.

Now consider the case of an under-filled sand-gravel mixture. By nature, the fluid finds the path of least resistance. The effect of this is the creation of "two" flow pathways within the gravel pore space, one through the sand and the other through the pore space that is free from the sand occupation. The two flow pathways run in parallel just like two parallel pipes of different diameters. This leads to an expression for the hydraulic conductivity of the mixed sediment as

$$k_{under\text{-}filled} = k_g(1 - \xi)^2 + k_s n_g \xi \tag{3.6}$$

where

$$\xi = \frac{(1 - n_g)\lambda}{n_g (1 - n_s)(1 - \lambda)} \tag{3.7}$$

In the case of the over-filled state, the gravel particles simply act to reduce the cross-sectional area of the sand media. The corresponding hydraulic conductivity may then be given by

$$k_{over\text{-}filled} = \frac{k_s \lambda}{\lambda + (1 - n_s)(1 - \lambda)} \tag{3.8}$$

At the critical sand percentage, the hydraulic conductivity is

$$k_c = n_g k_s \tag{3.9}$$

In general, the hydraulic conductivity of a mixed sand-gravel media may be estimated by

$$\begin{cases} k = k_g(1 - \xi)^2 + k_s n_g \xi & (\lambda \le \lambda_c) \\ k = \dfrac{k_s \lambda}{\lambda + (1 - n_s)(1 - \lambda)} & (\lambda \ge \lambda_c) \end{cases} \tag{3.10}$$

3.4 Bulk Density

The bulk density of the sand-gravel mixture can be easily worked out from the porosity as calculated using equation (3.5):

$$\begin{cases} \rho_{bulk} = \dfrac{(1 - n_g)\rho_s}{1 - \lambda} & (\lambda \le \lambda_c) \\ \rho_{bulk} = \dfrac{(1 - n_s)\rho_s}{1 - n_s(1 - \lambda)} & (\lambda \ge \lambda_c) \end{cases} \tag{3.11}$$

3.5 Comparison with Experimental Results

3.5.1 Permeability experiment

In order to validate equations (3.5) and (3.10), a series of permeability tests were carried out at the University of Brighton. Although Mason (1997) performed permeability tests for sand-gravel mixtures of varying sand content, the data could not be used due to lack of information on porosity. Similarly, the data of Blanco (2003) contained porosity but permeability was not measured. Using as a guideline the theoretical predictions and the results from Mason (1997), we decided to test sand-gravel mixtures with sand content at 0%, 10%, 20%, 30%, 40%, 60%, 80% and 100% by weight. The gravel had a D_{50} of 4 mm while three sand sizes were used, representing the fine, medium and coarse range. The size distribution of the gravel and sands is shown in Figure 3.1. The test procedure followed that of British Standard 1377 (BSI, 1990). A constant head permeameter was used, which has a cell chamber of 75 mm diameter and 600 mm length with three manometer tappings spaced at 225 mm apart.

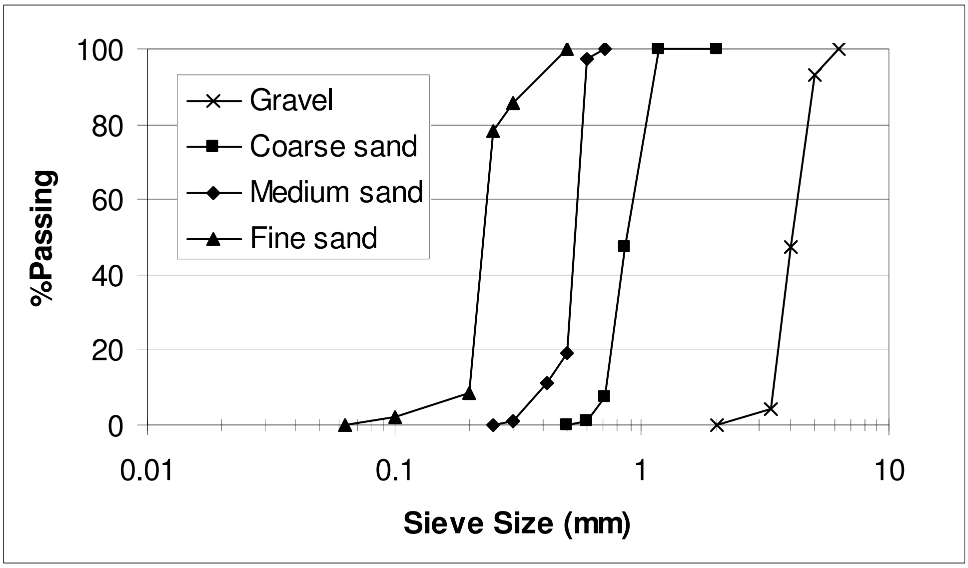


Figure 3.1 Sediment grading of sand and gravel used for permeability tests

3.5.2 Comparison between theory and experimental data

Figure 3.2 compares the porosity measured from the current permeability tests with the prediction given by equation (3.5). The measured data followed the trend as predicted by the equation, but the minimum porosity appears to occur at the critical point. The test data of Blanco (2003) does not contain the porosity for pure sand. Given the fact that fine sand was used in Blanco's experiment, we assume a value of sand porosity as measured in the current experiment for fine sand. This allows a comparison between Blanco's test data with the prediction by equation (3.5), as shown in Figure 3.3. Again, the analytical solution gives very good prediction against the experimental data.

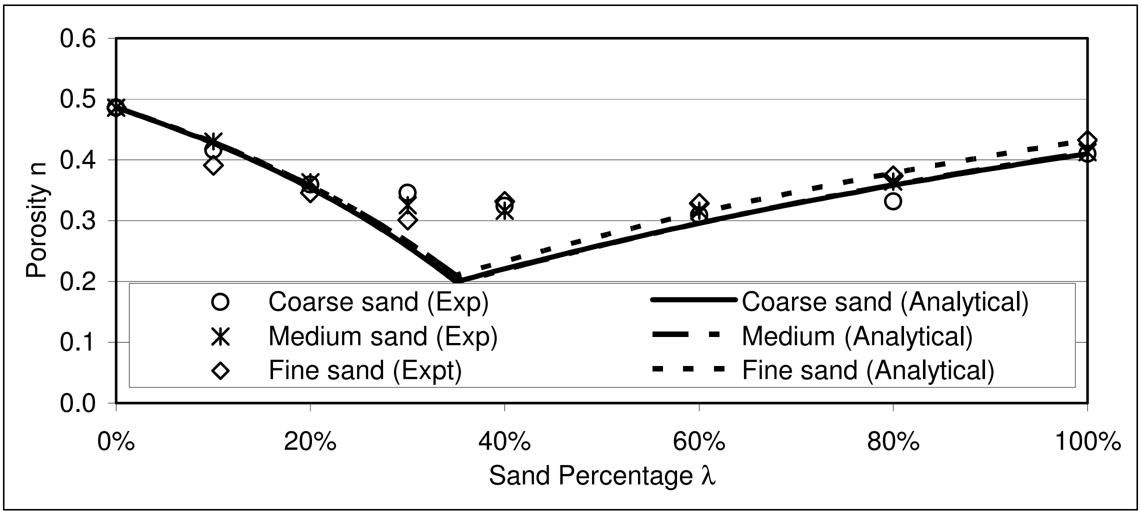


Figure 3.2 Comparison between analytical prediction and measured porosity (present study)

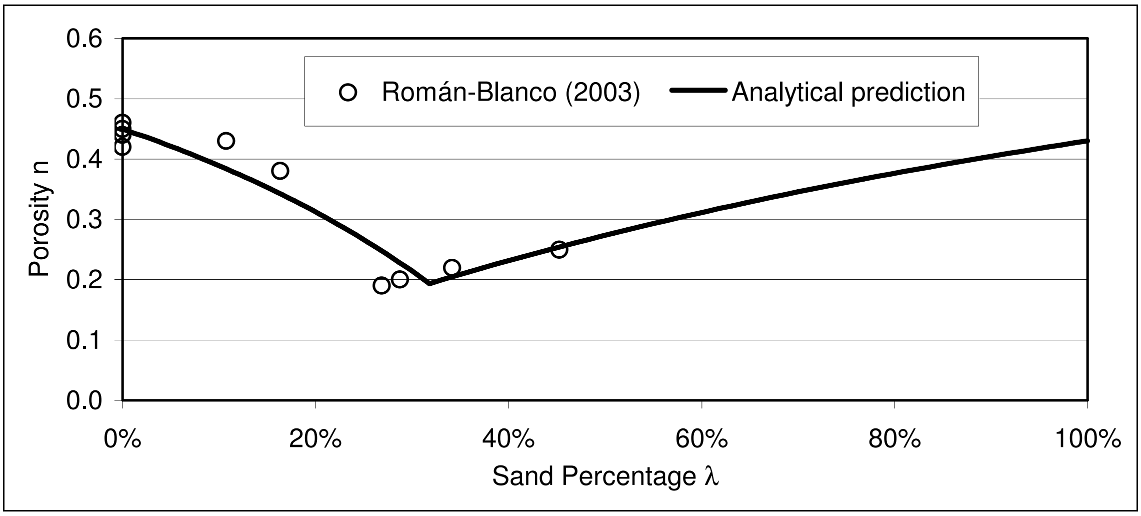


Figure 3.3 Comparison between analytical prediction and measured porosity of Román-Blanco (2003)

Figure 3.4 shows the currently measured hydraulic conductivity in comparison with the predictions by equation (3.10). It can be seen that there is very good agreement between the test data and analytical prediction across the whole range of sand percentages for all three sand sizes. In addition, there is also good agreement between the theoretical predictions and the experimental results of Mason (1997), as shown in Figure 3.5. Note that Mason's experiment did not include measurements of porosity. However, the gravel size D_{50} in Mason's experiment is the same as that used in the present study, while the sand sizes are also similar. As a result, we used the porosity values obtained from the present experiment when producing the analytical curves in Figure 3.5.

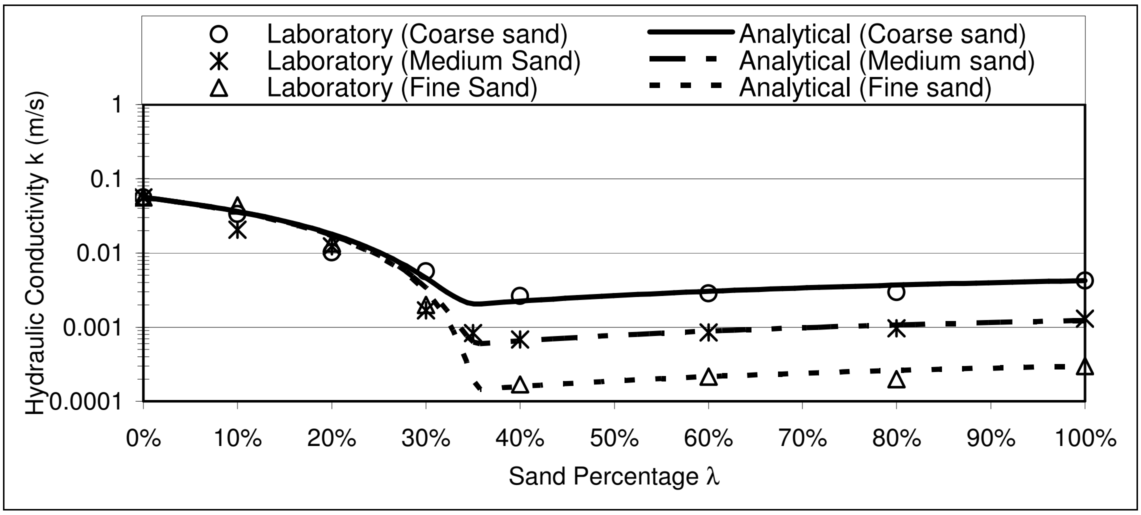


Figure 3.4 Comparison between analytical prediction and measured permeability (present study)

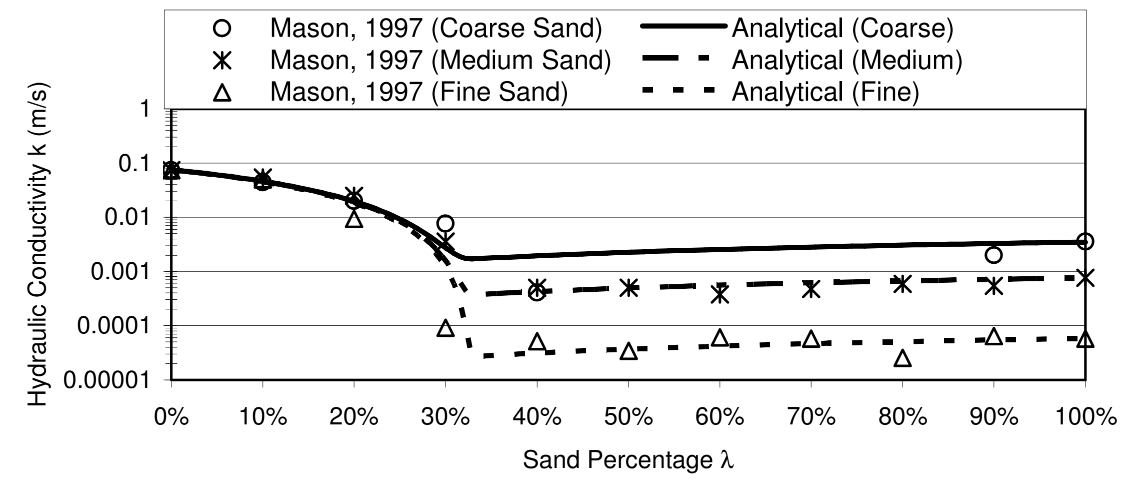


Figure 3.5 Comparison between analytical prediction and measured permeability of Mason (1997)

3.5.3 Discussions on porosity and hydraulic conductivity

Having shown the validity of the analytical solution, we can now look at the significance of the derived equations. The first important point is that as the sand content increases from 0% to the critical value λ_c, the hydraulic conductivity reduces rapidly. This effect can be better seen from Figure 3.6, which shows the ratio between the hydraulic conductivity of sand-gravel mixtures and that of pure gravel. A major advantage of a gravel beach is its ability to efficiently absorb wave energy over a short distance as a result of large percolation flow allowed in the beach. This advantage over sand beaches quickly disappears as the increased sand fraction is added to the gravel.

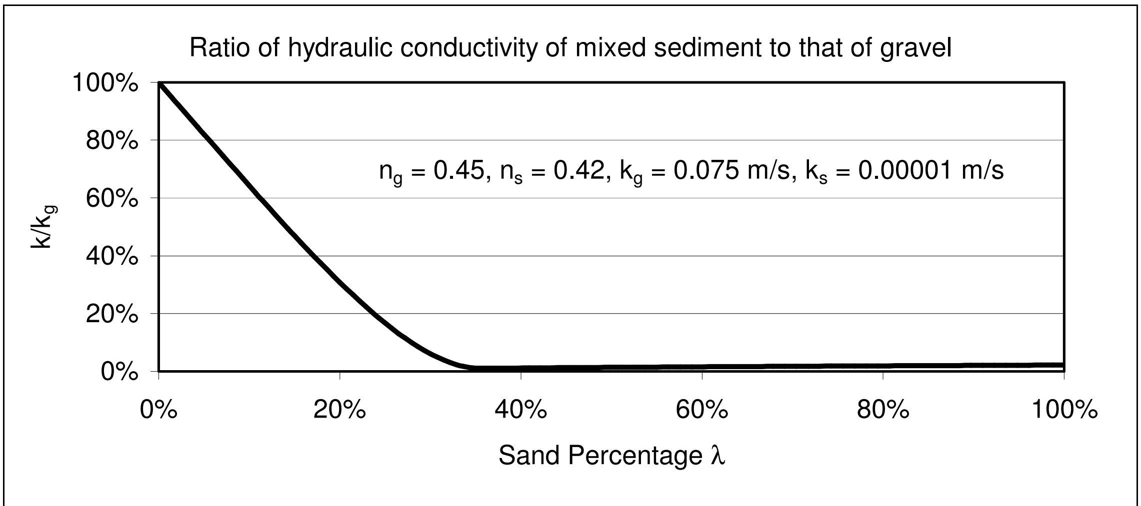


Figure 3.6 Relative hydraulic conductivity as a function of sand percentage

Note that the hydraulic conductivity reaches a minimum at the critical sand percentage. As the sand percentage increases further, the hydraulic conductivity rises gradually but remains below the value of pure sand. The minimum hydraulic conductivity means that the percolation flow in the beach is also at a minimum. As a result, the beach's ability to dissipate wave energy by percolation flow is at its worst. From this point of view, the critical point represents the worst possible case in terms of beach performance.

3.6 Loading Experiment and Implications on Cliffing

The particular nature of porosity, bulk density and permeability of the sand-gravel mixture as a function of sand percentage seems to indicate that serious cliffing starts to occur when the sand fraction is equal or more than the critical value. The critical point is also likely to be the worst point for cliffing. To verify this hypothesis, we carried out some simple but effective laboratory tests. The experiment was intended to be indicative rather than definitive. The experimental procedure is as follows:

a) Weigh the amount of dry sand and gravel according to the required sand percentage, and mix the two by hand.

b) Place the mixture in a (63µm) sieve and add water into the sand-gravel mix. Allow the excess water to drain and then mix content again.

c) Place the sand-gravel mixture into a plastic container in layers of ~5cm, hand-tamping each layer as happened in the permeability experiment. The container is 185 mm diameter and 120 mm height with a wall slope of 1:15.

d) Place a laminated chipboard on the top of the container, turn the board and container upside down and lay them on a level concrete base.

e) Slowly remove the container to form a "sand castle".

f) If the sand castle does not collapse, place an empty container on top of the "sand castle". Slowly add gravel into the container until the "sand castle" collapses.

g) Record the load at which the "sand castle" collapses.

We chose to experiment with the medium sand and gravel mixture, with the sand content of 20%, 30%, 36%, 40%, 50% and 100%. The 36% represents the critical point. Each mixture was tested twice. At 20% and 30%, the "sand castle" collapsed on removing the container. In both cases, the collapse was symmetric, as shown in Figures 3.7 and 3.8, but the central portion of the "sand castle" remained upright. As can be expected, the size of the free standing part of the "sand castle" became smaller as the sand percentage was reduced. In addition, this remaining part completely collapsed when experiencing minor disturbance.

Figure 3.7 Collapsed "sand castle" (λ=20%)

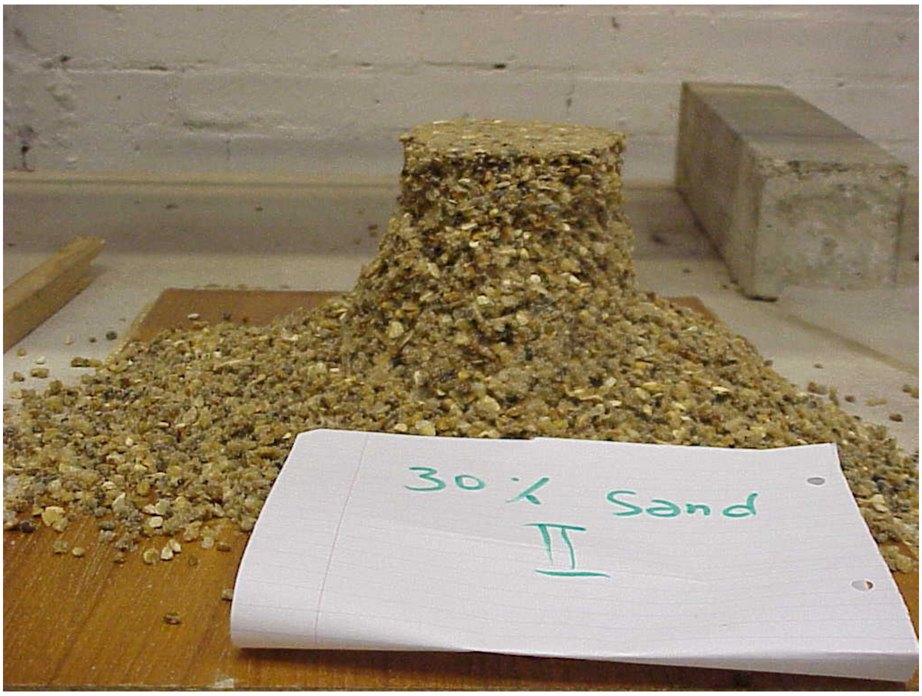


Figure 3.8 Collapsed "sand castle" (λ=30%)

At 36 and higher percentages, the "sand castles" stood firm on removal of the container. The recorded failure load varied from sample to sample for a given sand percentage, and from one sand percentage to another. Figure 3.9 shows the 40% "sand castle" at different stages of the test. Figures 3.10 to 3.13 show the collapsed "sand castles" under load at various sand percentages. In all cases tested, the collapses were asymmetric, which may have been caused by the imperfections (non-symmetric) in the "sand castle" itself and/or in the loading application.

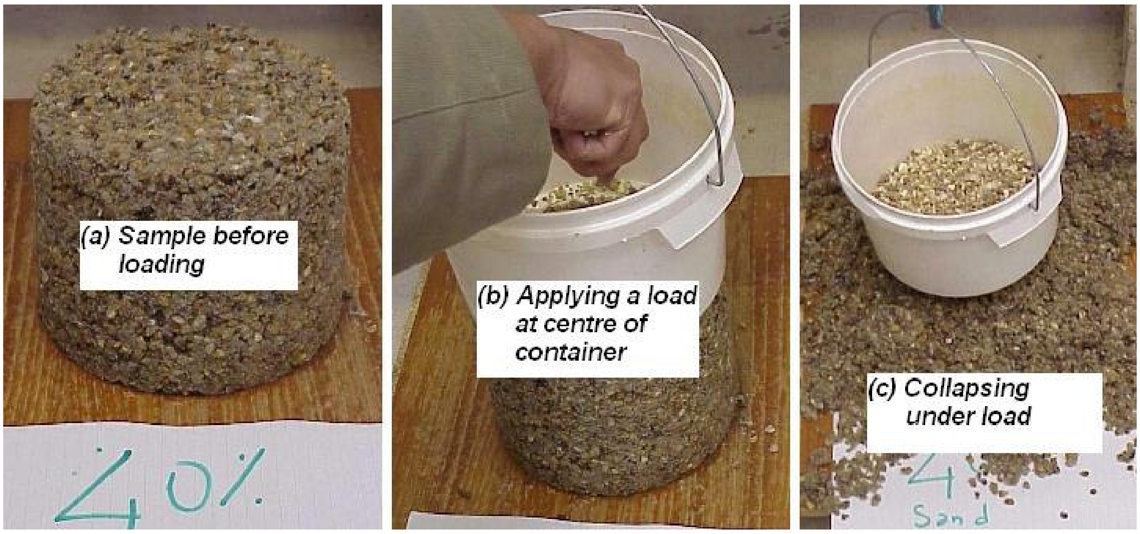


Figure 3.9 Different stages of "sand castle" test (λ=40%)

Figure 3.10 Collapsed "sand castle" (λ=36%)

Figure 3.11 Collapsed “sand castle” (λ=40%)

Figure 3.12 Collapsed “sand castle” (λ=50%)

Figure 3.13 Collapsed "sand castle" (λ=100%)

Table 3.1 summarises the collapsing loads for all tests. It seemed that the "sand castle" at the critical percentage was able to sustain a similar or greater load than at higher sand percentages. The reason for this may be due to the fact that the bulk density of the mixed sediment is at its highest (equation 3.11), and its behaviour is the closest to that of a solid body.

The implication of the "sand castle" experiment is that cliffing is likely a phenomenon which occurs when the sand percentage of the sediment exceeds the critical percentage. No serious cliffing should be expected below the critical percentage.

Table 3.1 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

3.7 Effects of Compaction

When recharging a beach, the sand-gravel mixture is greatly consolidated and compacted during the course of its placement onto the beach. This will significantly reduce the porosity of the sediment media, which in turn reduces the permeability and shifts the critical point to a lower percentage. This can be best demonstrated by Figures 3.14 and 3.15 showing the performance of mixed sediment assuming 10% and 20% compactions. A basic assumption has been made here with regard to the effect of porosity on the permeability. According to Kozeny (1927), the hydraulic conductivity may be approximated by

$$k = \frac{Cd^2n^3}{(1-n)^2}$$

where C is a constant and d is the sediment size. Given a percentage reduction in the porosity, the reduction in the permeability of the sand and gravel may be worked out accordingly. It can seen that with a 20% compaction, the critical point is moved from 36% to 30%. The greater the compaction, the more reduction in the critical sand percentage. This also means that cliffing may occur at lower sand percentages.

In addition to the shift of the critical point, the compaction also has the effect of increasing the loading capacity of the sediment mix. This point can be demonstrated by the result of two additional tests at 50% and 100% sand where a greater tamping force was applied in making these “sand castles”. The failure load was increased by 250% for the 50% “sand castle” and 350% for the 100% “sand castle”.

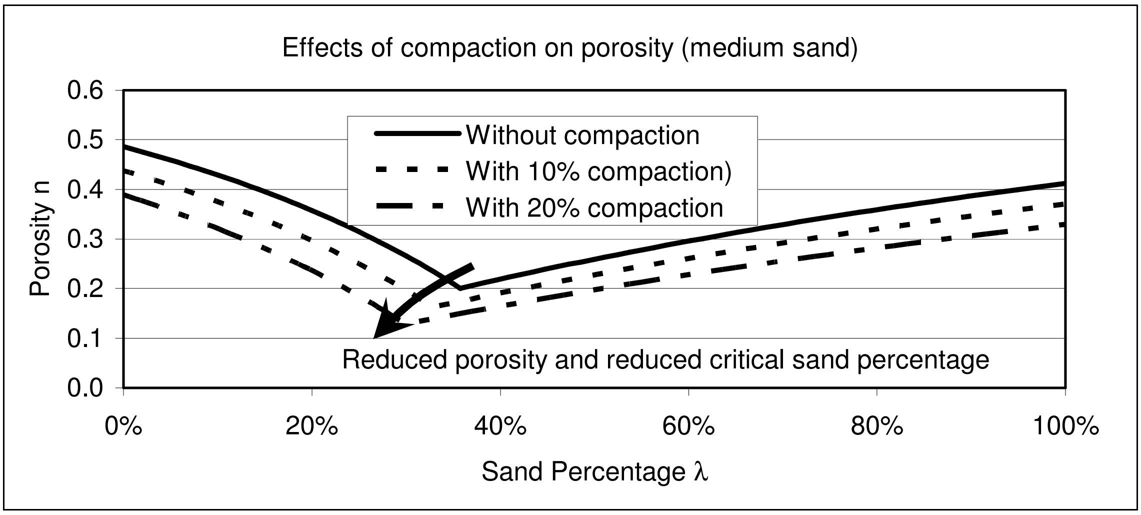


Figure 3.14 Effects of compaction on porosity

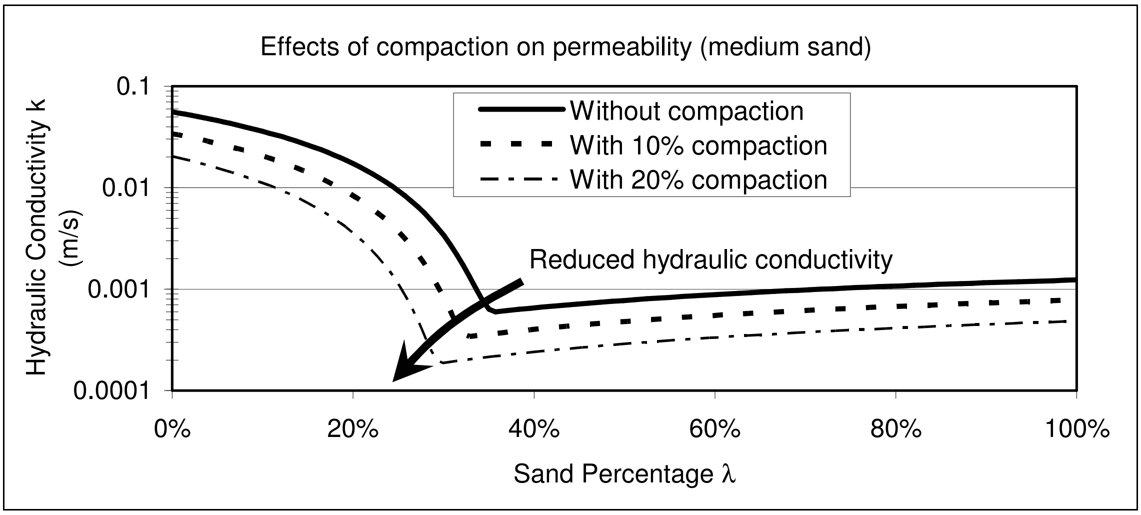


Figure 3.15 Effects of compaction on hydraulic conductivity

3.8 Summary

A set of analytical equations have been derived expressing the porosity and permeability of a bi-modal mixed sand-gravel sediment in relation to the sand percentage and the porosity and permeability of the component gravel and sand fractions. A critical sand percentage or critical point can be identified given the sediment properties of the component sand and gravel. At the critical point, the permeability and porosity of the mixed sediment reach their respective minimums while the bulk density is at a maximum. There are two important implications in terms of engineering applications. The first is that cliffing becomes a problem when the sand percentage exceeds the critical value. The second is that compaction will reduce the critical sand percentage at which cliffing starts to happen while increasing the loading capacity of the sediment mix.

4. Performance of Gravel and Mixed Beaches

4.1 Introduction

This report looks at how the performance of a beach may be influenced by a change in the permeability (hydraulic conductivity) of the beach material by examining existing experimental data collected at the University of Brighton (Trim 2003). The laboratory work included two parallel beach models at a scale of 1:30, with one reflecting 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}). As a result any behavioural differences may be broadly linked to the differences in the permeability of the beaches.

4.2 The Beach Model

The experiments were carried out in a wave flume of 10m in length, 0.45m in width and 0.5m in depth. The model material was graded anthracites with a density of 1400 kg/m^3. The model setup is shown in Figure 4.1, and the sediment characteristics of the two beaches are shown in Figure 4.2. At the 1:30 scale, the mixed beach model represents 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.

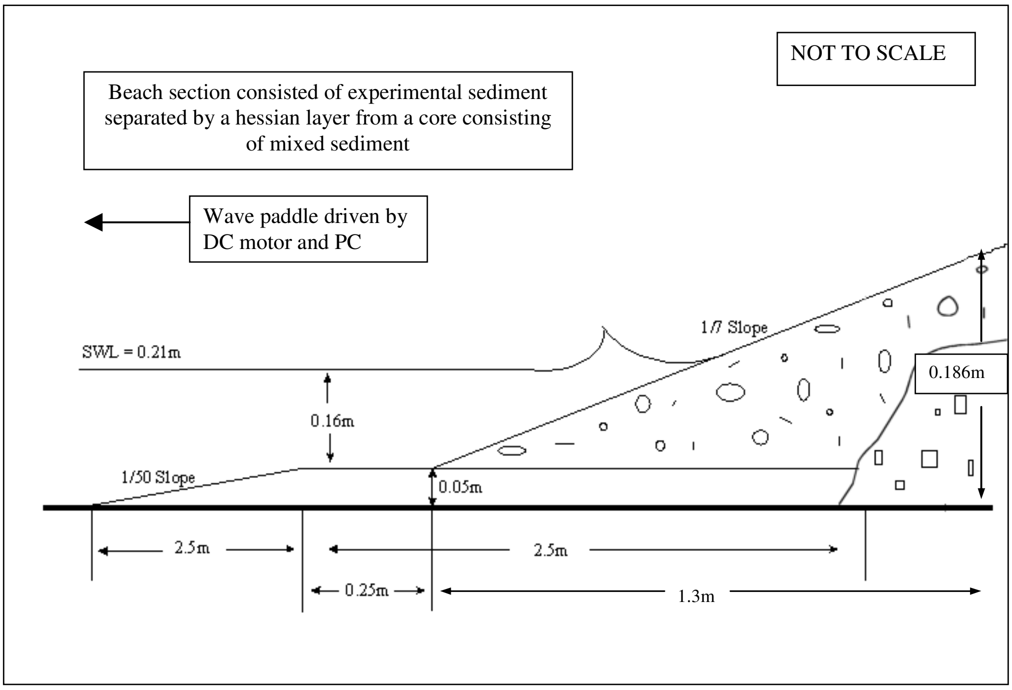


Figure 4.1 Schematic of beach model set-up

Figure 4.2 Sediment characteristics of beach models

4.3 Test Conditions

Waves were produced by a PC operated DC piston-type wave generator supplied by HR Wallingford. The test conditions included both monochromatic and random waves of a range of wave height and period, as given in Table 4.1. The random waves were generated based on the Jonswap Spectrum. Both model beaches were subjected to each wave condition for a duration of 30 minutes, which is approximately 3 hours under prototype conditions.

Table 4.1 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

With an initial slope of 1:7, the beach profiles were manually measured at 10 minute intervals. This was done by marking the profiles with coloured markers onto the glass sidewalls of the tank during the test. At the end of each test, the marked profiles were measured and recorded. Each profile consisted of an elevation measurement for each 50mm chainage to an accuracy of 1mm. Differences were present between the profile readings on the two sidewalls. Complete symmetry in the evolution of a 2D beach model can never be attained, partly due to the imperfections in the initial beach slope and partly due to the variations of sediment sizes across the beach. As a result, the average readings of the two walls are used for the final analysis.

4.4 Results and Discussions

In general, the beach underwent rapid changes within the first few minutes and a pseudo-steady state was attained after 10 minutes, as demonstrated in Figures 4.3 and 4.4. Both summer and storm profiles were observed under both monochromatic and random wave conditions. The general trend of profile evolution was similar for both model beaches but there were significant differences in the quantity of sediment movement. The first difference is that, where onshore transport took place, the mixed beach experienced less movement of material. This can be clearly seen from Figures 4.5, 4.6 and 4.7 under monochromatic wave conditions, and Figures 4.8, 4.9 and 4.10 under random wave conditions. In the case of offshore transport, the profiles of the mixed beach showed greater losses of material from the beach head. This may be seen from Figures 4.11, 4.12 and 4.13 under monochromatic wave conditions, and Figures 4.14, 4.15 and 4.16 under random wave conditions.

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. 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 during the uprush and that taken down 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 head. 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.

4.5 Summary

Two implications may be drawn from the analysis of Trim's (2003) experimental data. The first 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 is of great significance in influencing the sediment transport processes on the beach. The greater the sand percentage, the smaller the hydraulic conductivity and the more impaired the beach is as compared to a gravel beach.

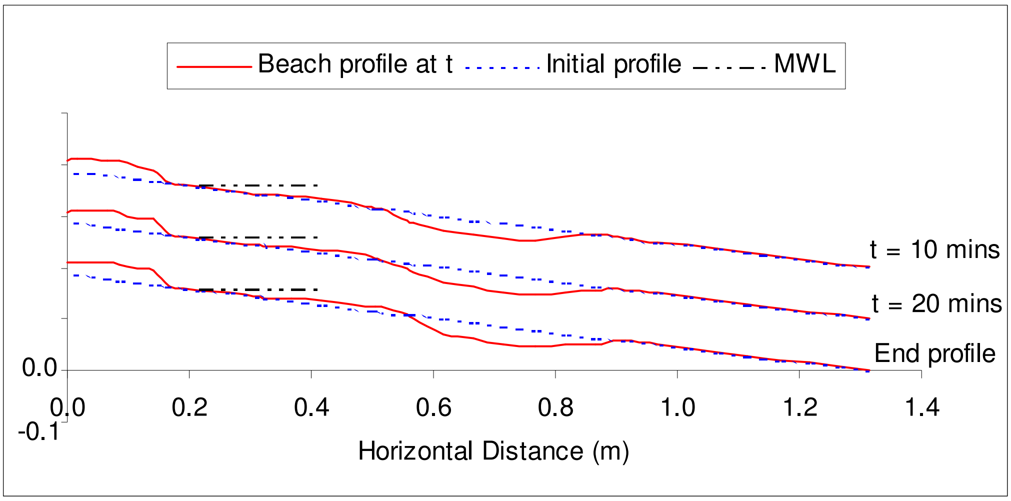


Figure 4.3 Profiles recorded under monochromatic wave conditions (Condition B: f=0.53Hz, H_s=0.04m) with a mixed beach model

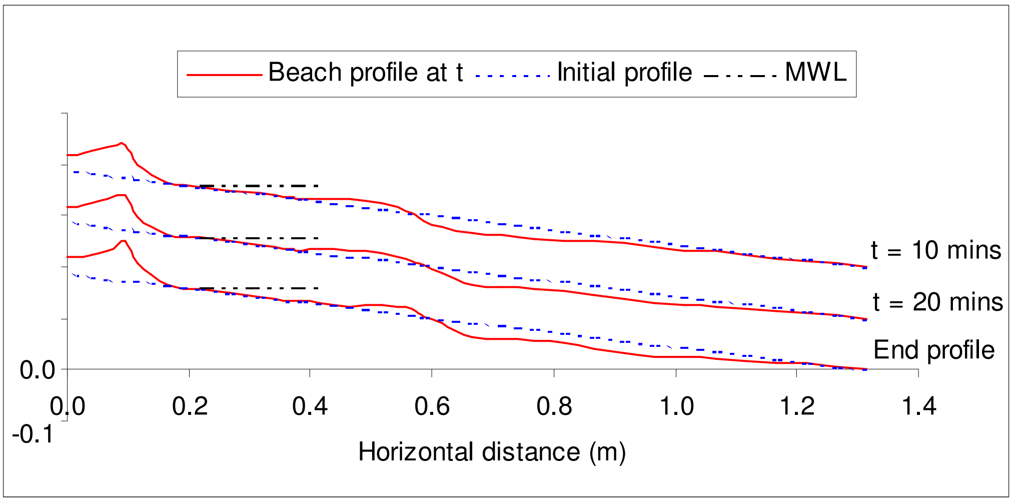


Figure 4.4 Profiles recorded under random wave conditions (Condition I: f=0.53Hz, Hs=0.052m) with a mixed beach model

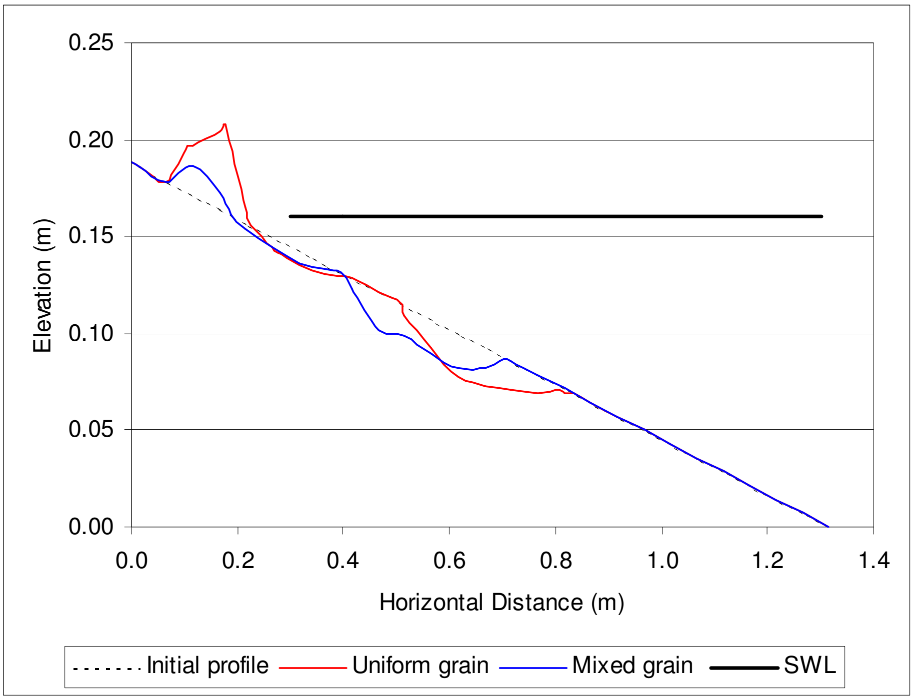


Figure 4.5 Comparison of gravel (uniform grain) and mixed beach profiles (Monochromatic wave conditions A: f=0.53Hz, H_s=0.02m)

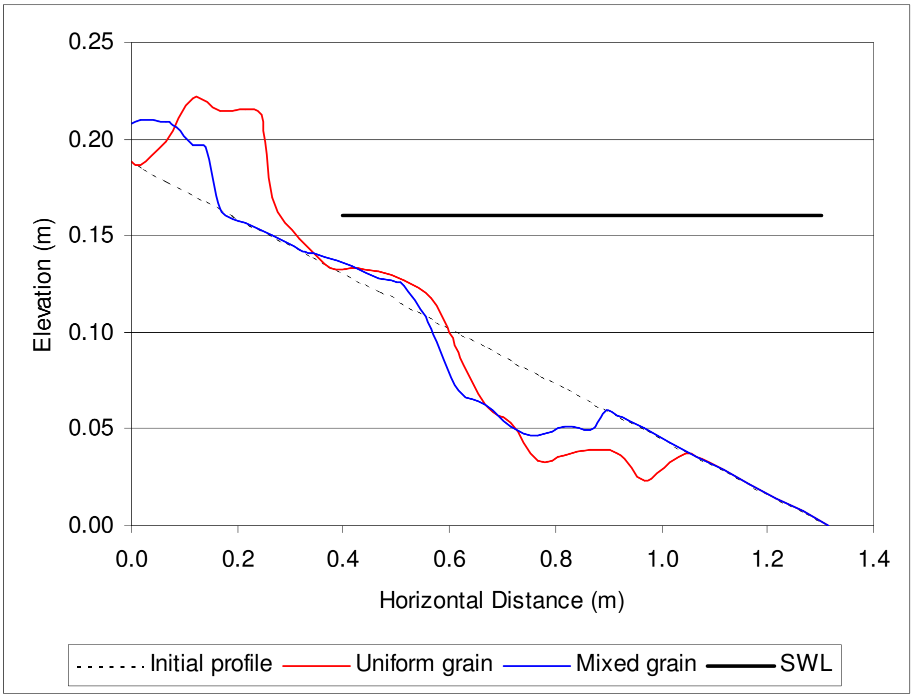


Figure 4.6 Comparison of gravel (uniform grain) and mixed beach profiles (Monochromatic wave condition B: f=0.53Hz, H_s=0.04m)

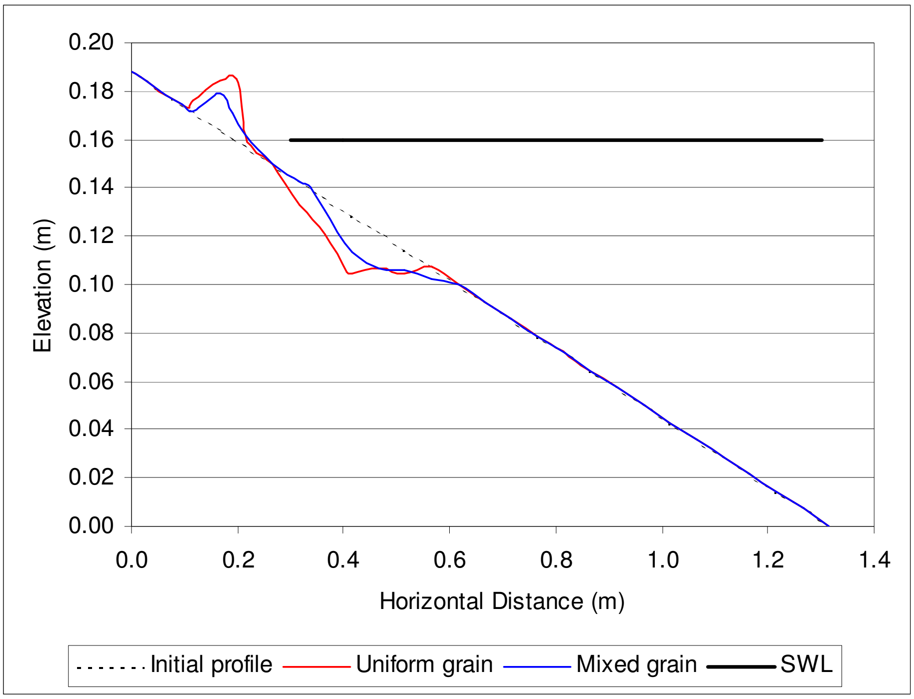


Figure 4.7 Comparison of gravel (uniform grain) and mixed beach profiles (Monochromatic wave condition C: f=1.05Hz, H_s=0.02m)

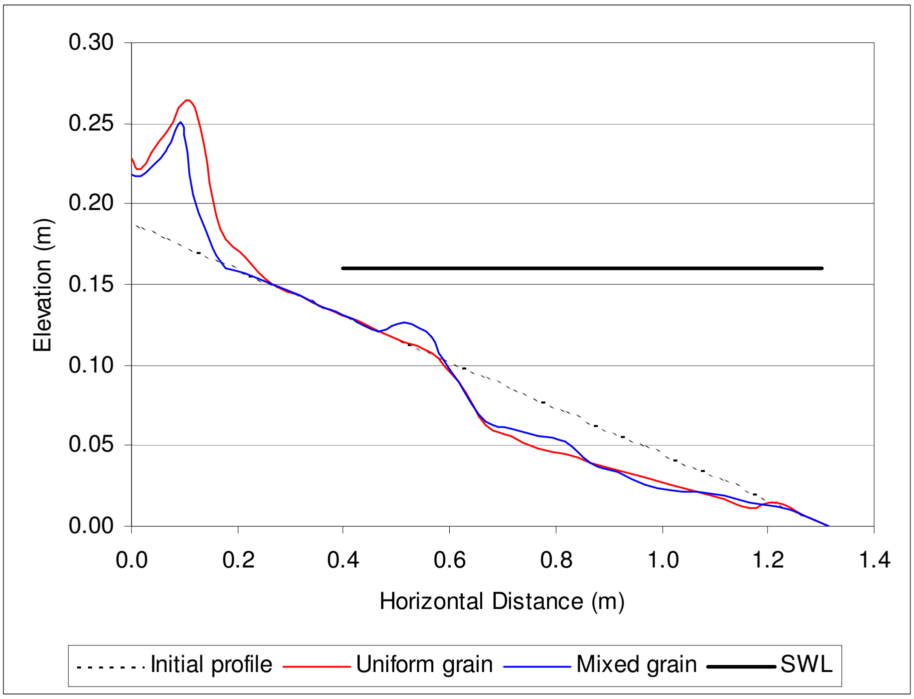


Figure 4.8 Comparison of gravel (uniform grain) and mixed beach profiles (Random wave condition I: f=0.53Hz, H_s=0.052m)

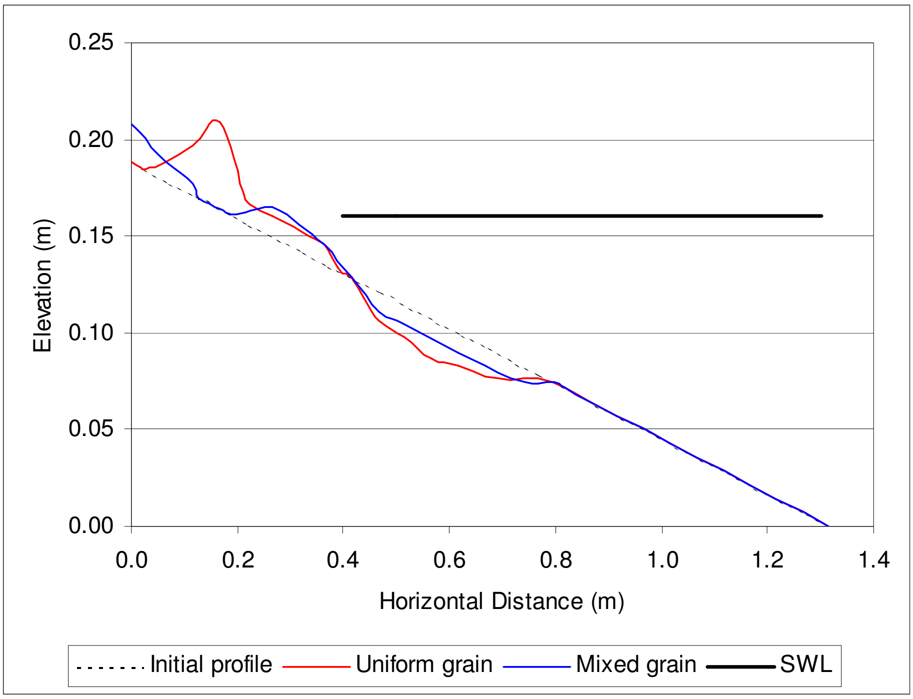


Figure 4.9 Comparison of gravel (uniform grain) and mixed beach profiles (Random wave condition K: f =1.05Hz, H_s=0.033m)

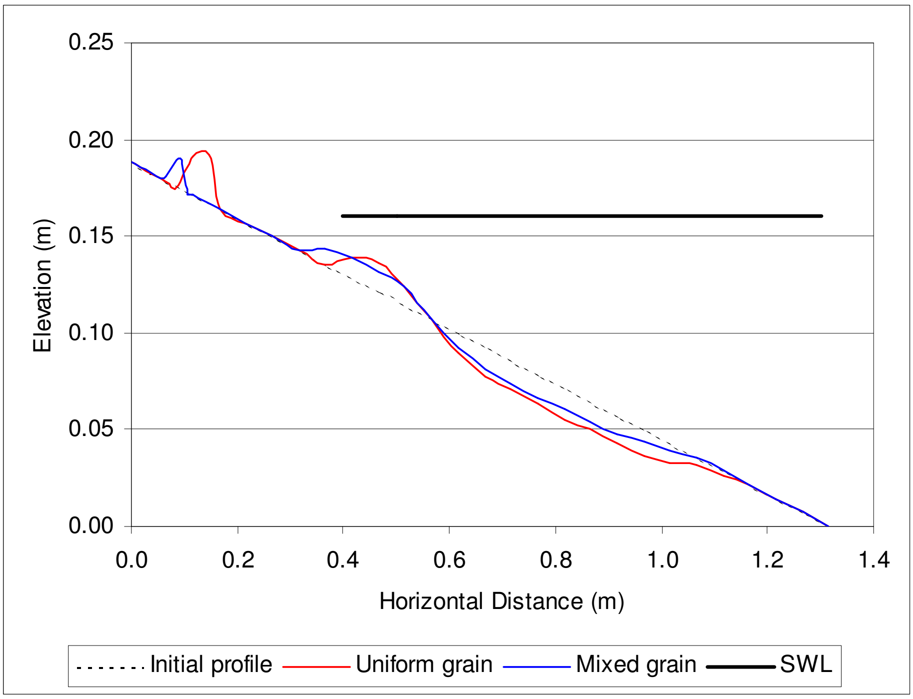


Figure 4.10 Comparison of gravel (uniform grain) and mixed beach profiles (Random wave condition L: f=1.05Hz, H_s=0.053m)

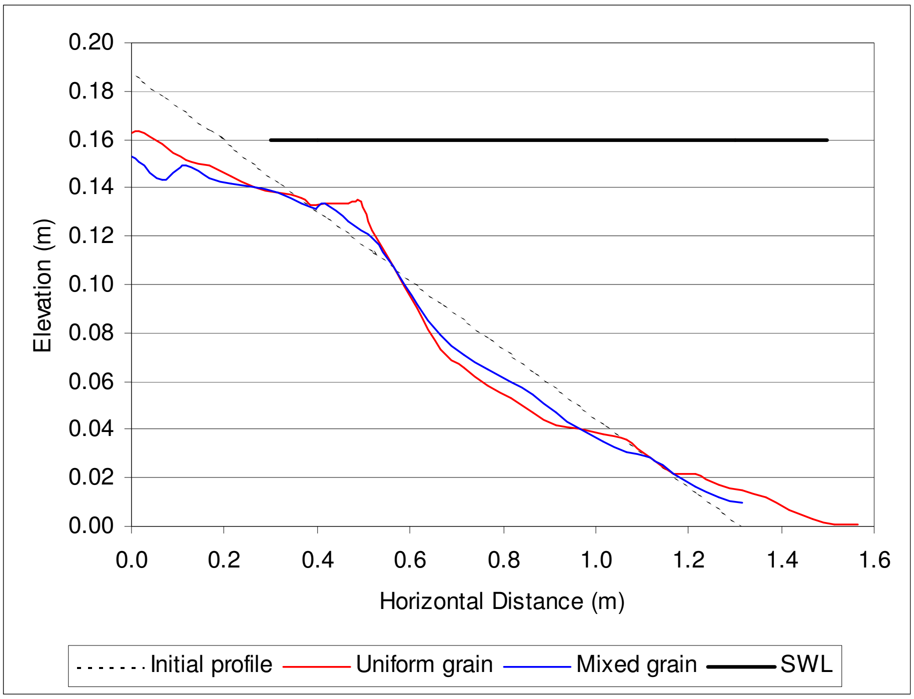


Figure 4.11 Comparison of gravel (uniform grain) and mixed beach profiles (Random wave condition E: f =1.05Hz, H_s=0.06m)

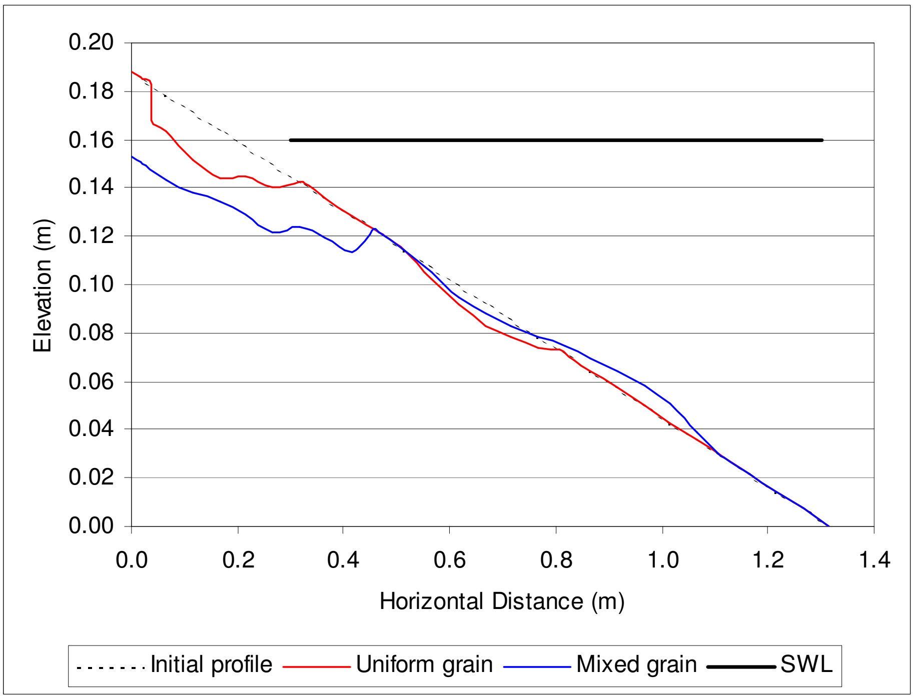


Figure 4.12 Comparison of gravel (uniform grain) and mixed beach profiles (Monochromatic wave condition G: f =1.58Hz, H_s=0.04m)

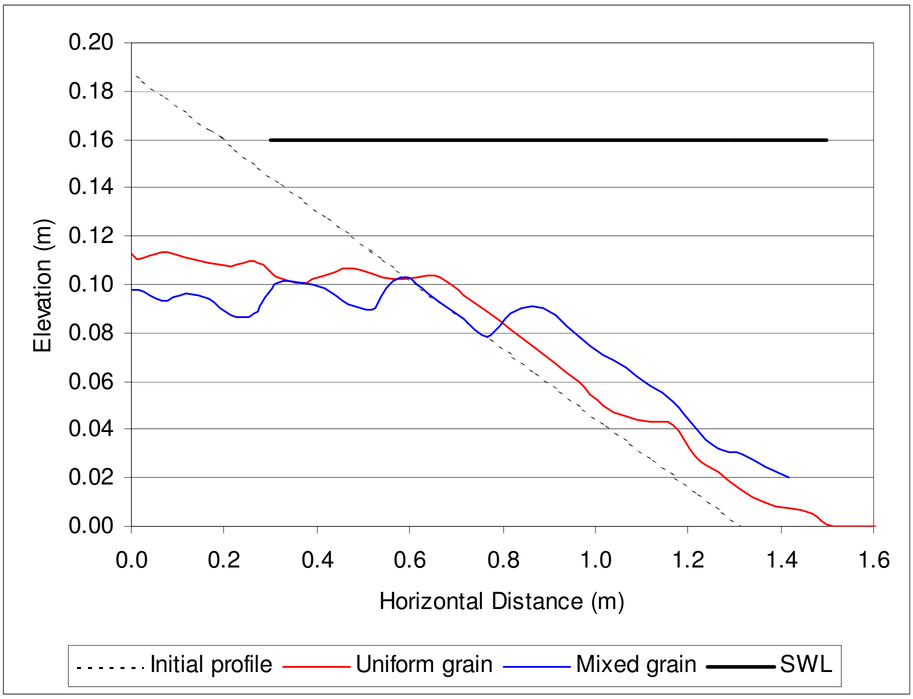


Figure 4.13 Comparison of gravel (uniform grain) and mixed beach profiles (Monochromatic wave condition H: f=1.58Hz, H_s=0.06m)

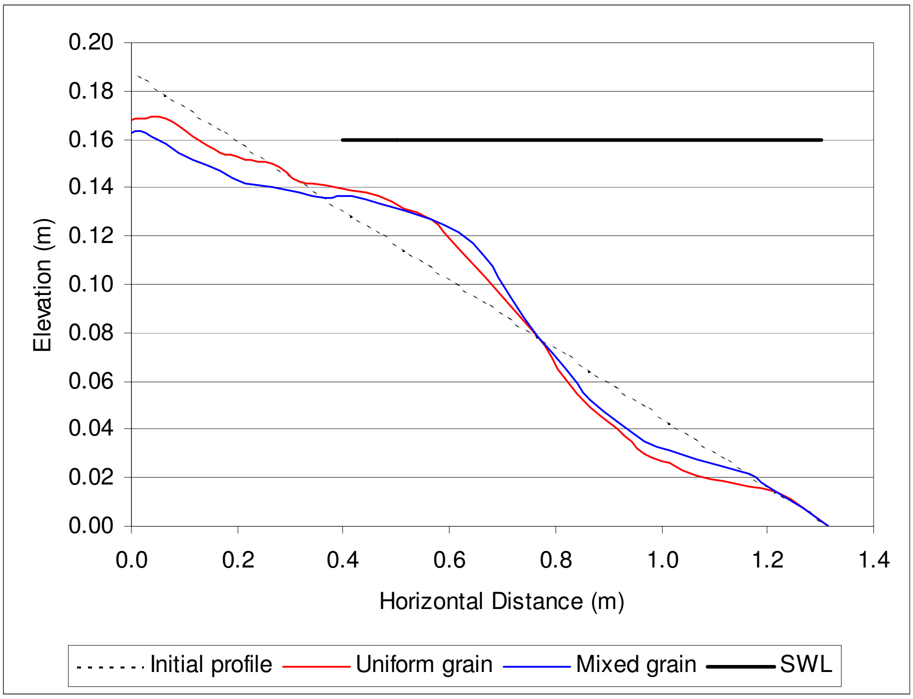


Figure 4.14 Comparison of gravel (uniform grain) and mixed beach profiles (Random wave condition J: f=0.53Hz, H_s=0.084m)

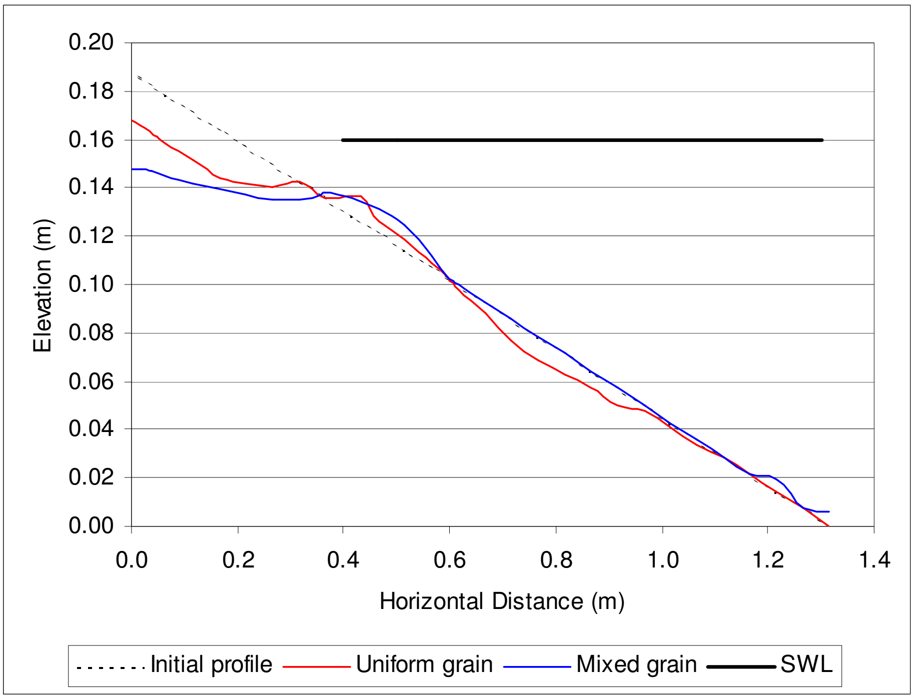


Figure 4.15 Comparison of gravel (uniform grain) and mixed beach profiles (Random wave condition P: f=1.58Hz, H_s=0.052m)

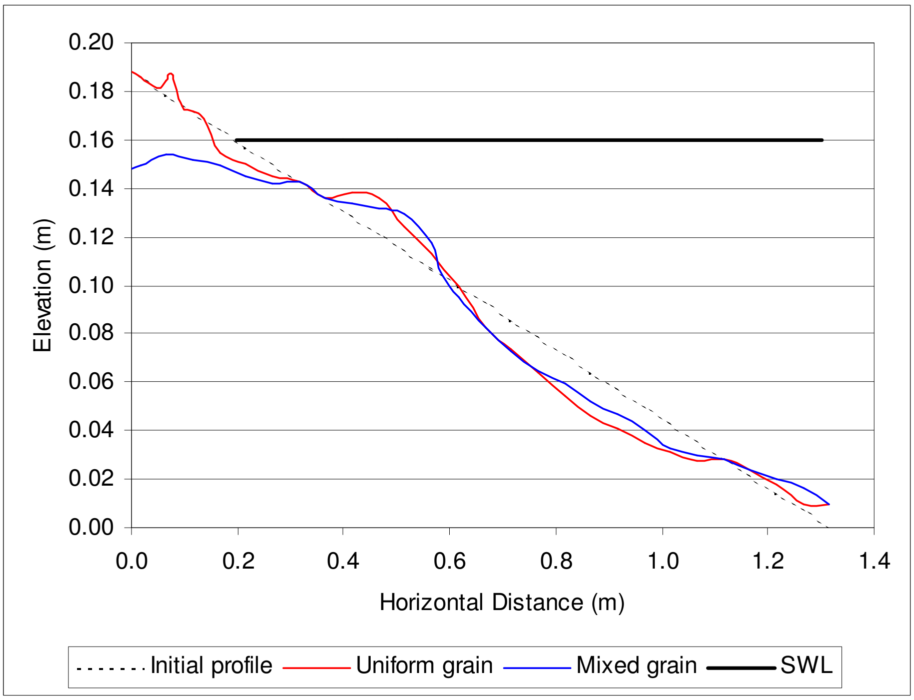


Figure 4.16 Comparison of gravel (uniform grain) and mixed beach profiles (Random wave condition M: f=1.05Hz, H_s=0.069m)

5. Influence of Groundwater Level on Beach Evolution

5.1 Introduction

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). Validation of the model under gravel beach conditions was carried out by Horn et al. (2003) and Horn and Li (2006). The BeachWin is selected for the current investigation because of our extensive experience in the use of the software. In addition, access to the software is free for this project.

In the BeachWin model, the transformation of waves across the nearshore zone and the motion of swash are modelled using the non-linear shallow water equations (SWE; Peregrine 1972). Modifications of the SWE are made to account for the mass and momentum exchange between seawater and beach groundwater due to infiltration/exfiltration. Bottom friction is included by using the quadratic approximation, $\frac{1}{2} f|u|u$, where *f* is a friction factor and *u* is the flow velocity (Packwood and Peregrine 1981). Only the saturated beach groundwater flow, as governed by the Laplace equation, is considered in the model. However, the capillary effects on the saturated flow are incorporated through the free-surface boundary condition at the water table (Li et al. 1997). The wave model is coupled with the groundwater flow model via the boundary conditions at the beach. For the groundwater flow, the seaward boundary conditions are determined by the shoreline position and the local sea surface elevation, both of which are calculated by the wave motion model. The rates of infiltration/exfiltration across the beach are computed by the groundwater flow model based on Darcy's law and then inputted to the wave model. In gravel beaches where pore water flows may become turbulent (non-Darcian flows), high order/non-linear effects play a role, but Darcy's law captures the most important effects (lower order effects). The instantaneous sediment transport rate is calculated at each cross-shore grid point based on a modification of the Bagnold (1966) energetics model, using the velocity from the wave motion model. The sum of the instantaneous rates over a wave cycle gives the net sediment transport rate, which is used to predict the beach profile changes. The location of the nodes at the beach face in the groundwater flow model, and the local beach slope in the wave motion model and the sediment transport model, are then adjusted according to the beach deformation. The BeachWin model has been used to investigate the effect of infiltration/exfiltration on swash zone hydrodynamics and sediment transport on sand and gravel beaches (Masselink and Li 2001). Their simulations showed that on a relatively impermeable beach (fine sand, K=0.01 cms^{-1}), beach profile development was characterised by offshore sediment transport resulting in steepening of the beachface and the formation of a bar/step feature below the still water level. On a permeable beach (gravel, K=1.6 cms^{-1}), the beach profile showed onshore transport and development of a bar/step feature at the beginning of the simulation, followed by onshore transport and berm development. However, these simulations were not validated against field or laboratory data.

5.2 Model (BeachWin) tests against field data

Horn et al. (2003) and Horn and Li (2006) tested the predictions of BeachWin against data from a gravel beach (Slapton Sands, Devon). The beach was composed of relatively uniform gravel with a mean size of 9 mm and a steep slope of 9.8° ($\tan\beta$=0.17). Surface and subsurface pressures were measured with twelve pressure transducers deployed in different configurations to obtain measurements at a range of vertical and horizontal positions. Bed levels were measured every 10 minutes for nine hours over both a rising and a falling tide. BeachWin was used to simulate the field experiment in order to examine the beach groundwater response to waves and beach profile change. Although some of the model assumptions are not necessarily correct for gravel beaches (particularly the assumption of Darcian flow), the simulated pore pressures captured the main features of the wave motion, with most peaks of the measured water depths predicted by the model, especially the time of occurrence. However, the model over-predicted pore pressures in the swash zone. Simulations of beach profile response with and without infiltration were compared to measured beach profile change. The model predicted the observed berm formation on the upper part of the beach, suggesting that swash infiltration played an important role in the short-term profile evolution of a gravel beach; however, the predicted erosion area was landward of the measured erosion area. Horn and Li (2006) also used the BeachWin model to look at the effect of varying hydraulic conductivity, friction factor, and k_u/k_b (calibration coefficients for the Bagnold energetics model, relating the ratio of uprush and backwash sediment transport rates, as in Masselink and Hughes 1998). Their simulations showed that accretion on the upper beachface increased with hydraulic conductivity and k_u/k_b, and decreased with friction factor.

5.3 Model (BeachWin) tests against laboratory data

The experiments were carried out in a section of the Coastal Wave Basin in the Department of Civil Engineering, University of Queensland, Australia. The section used in the experiments reported here was 27.3 m long,1.4 m wide and 0.8 m deep (Figure 5.1). The experiments were carried out with a working depth of 0.5 m. The water level in the basin was kept constant using a small inflow near the wave generator and a weir behind the beach. The back of the beach was supported by a wire mesh located 0.2 m from the back wall of the flume, which prevented the loss of sediment while allowing water flow in and out of the permeable beach. The water level behind the beach was controlled by an adjustable pipe which was connected through the back wall. A set of 20 damped manometer tappings on the bed of the flume provided time-averaged mean piezometric head levels in the cross-shore direction from offshore of the breakpoint to the back of the beach. The water level in the manometer tubes responded quickly to uprush and backwash, and eventually reached steady state conditions. Wave parameters were measured with two surface-piercing wave gauges.

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, with the beach gradient starting from the weir mesh and extending 5.4 m from the back wall. The beach was regraded between runs so that each run started with the same initial profile. 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 (Table 5.1). All tests were run for an hour. Manometer readings were taken at the start of the experiment and at 10, 20, 35 and 55 minutes into the run. The beach profile was measured along the centre line of the beach at the start of the experiment and at 15, 30 and 60 minutes into the run. In terms of flow through the beach, the coarse sand beach is comparable to a gravel beach at full scale. The scalings are shown in Table 5.2.

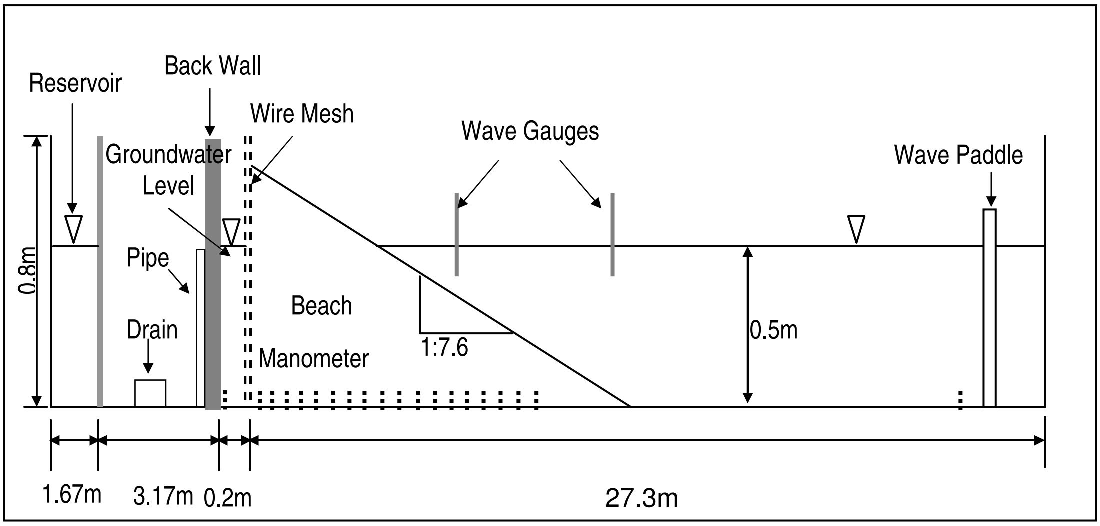


Figure 5.1 Wave flume, beach layout and instrumentation

On the coarse sand beach, with a lower watertable, a higher berm was formed in accretionary conditions (Figure 5.2). Under erosional conditions, slightly less erosion was observed on the upper beach, although little change was observed below mean sea level (Figure 5.5). A higher groundwater level promoted offshore sediment transport, with the associated formation of a smaller berm for swell profiles (Figure 5.4) and increased beachface erosion in storm conditions (Figure 5.7). 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 5.8 to 5.19). The model tends to underestimate groundwater levels for longer period waves and overestimate them for shorter period waves.

Table 5.1 Experimental runs for each grain size

Run	H (m)	T (Hz)	Ω (H_b/w_sT)	Profile type	GWL relative to SWL +0.05 m	GWL relative to SWL 0 m	GWL relative to SWL – 0.05 m
1	0.05	0.4	0.15	swell	0405p	0405z	0405m
2	0.10	0.4	0.31	swell	0410p	0410z	0410m
3	0.15	0.4	0.46	swell	0415p	0415z	0415m
4	0.05	0.6	0.23	swell	0605p	0605z	0605m
5	0.10	0.6	0.46	swell	0610p	0610z	0610m
6	0.12	0.6	0.7	swell/ storm	0612p	0612z	0612m
7	0.15	0.6	0.56	storm	0615p	0615z	0615m
8	0.05	1	0.39	storm	1005p	1005z	1005m
9	0.10	1	0.77	storm	1010p	1010z	1010m
10	0.15	1	1.16	storm	1015p	1015Z	1015m

Table 5.2 Model and prototype parameters

Lab parameter	Prototype (storm)	Prototype (swell)
Period (sec)	**Scaling 1:√10**	**scaling 1:√25**
2.50	7.90	12.50
1.67	5.28	8.35
1.00	3.16	5.00
Wave height (m)	**scaling 1:10**	**scaling 1:25**
0.05	0.50	1.25
0.10	1.00	3.75
1.00	1.50	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

5.4 Summary

Comparison between the BeachWin model and field data leads to following conclusions:

1. Comparison of measured and modelled pore pressures captured the main features of the wave motion, with most peaks of the measured water depths predicted by the model, especially the time of occurrence. However, the model over-predicted pore pressures in the swash zone.
2. Simulations of beach profile response with and without infiltration were compared to measured beach profile change. The model predicted the observed berm formation on the upper part of the beach, suggesting that swash infiltration played an important role in the short-term profile evolution of a gravel beach, particularly the berm formation; however, the predicted erosion area was landward of the measured erosion area.
3. Model simulations showed that the model predictions are sensitive to parameter values of the beach hydraulic conductivity, friction factor, and the ratio of uprush and backwash sediment transport rates, suggesting that these parameters play important roles in the beach profile changes at gravel beaches. Accretion on the upper beachface increased as hydraulic conductivity and ku/kb increased, whereas an increase in friction factor reduced the runup elevation and berm development. The simulations reported here give indications of possibly realistic values for these parameters.
4. The uncertainty over values of key model parameters highlights the importance of measuring these parameters as part of the field measurements whenever possible. In particular, hydraulic conductivity should be measured rather than estimated.

With respect to BeachWin model and laboratory tests, the following conclusions may be drawn:

1. Accretion above the SWL occurred at all groundwater levels on the coarse laboratory beach, suggesting that infiltration played a significant role in beach profile development. Onshore transport and berm development occurred under all inland groundwater levels, and particularly when the inland groundwater level was lowered.
2. Accretion above the SWL on the fine sand laboratory beach only occurred when the inland groundwater level was lowered. This suggests that altering the groundwater level is only able to induce accretion on an eroding profile on a fine sand beach, in contrast to previous suggestions that infiltration only plays a significant role in profile evolution on coarse-grained beaches and does not affect fine-grained beaches.
3. Although beach groundwater did influence profile evolution in almost all of the laboratory runs, the changes in groundwater elevation in these experiments were usually not sufficient to change an erosive profile to an accretive profile or vice-versa.
4. Onshore sediment transport in the laboratory experiments was enhanced when the groundwater level was lowered under both accretionary and erosive conditions, whereas 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 post-storm accretion on permeable beaches.

5. The data provide the first controlled experimental verification of a numerical model (BeachWin) which simulates wave and beach groundwater interaction in the coastal zone with forcing at wave frequencies. Profile evolution had little effect on measured or modelled head levels, which were primarily governed by the back beach head level and the wave runup limit. Agreement between measured and simulated head levels are better for the coarse beach due to greater infiltration. The main discrepancies between measured and simulated head levels appear to be a result of inaccurate prediction of the nearshore hydrodynamics rather than poor representation of the internal flow in the beach.

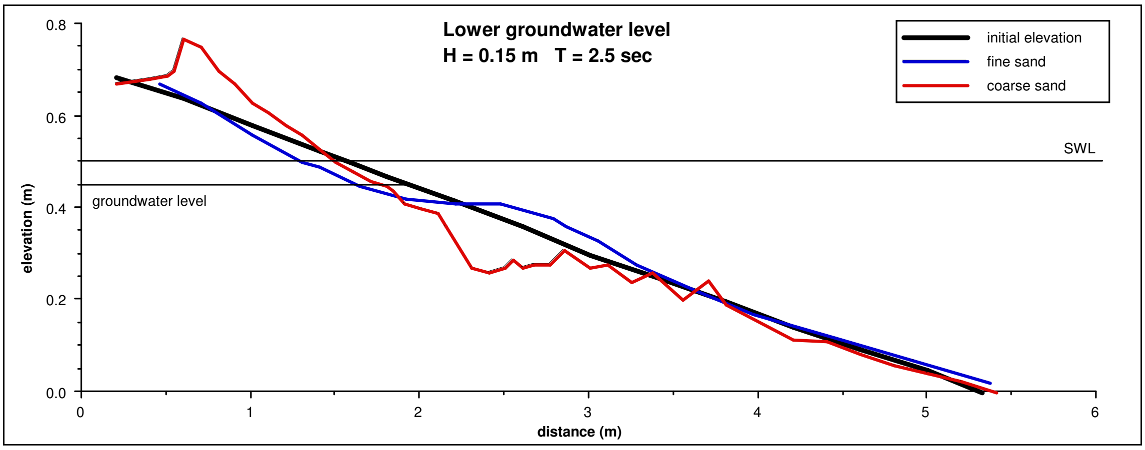


Figure 5.2 Comparison of fine and coarse sand profiles for swell conditions (T=2.5s, H=0.15m), inland groundwater level below SWL

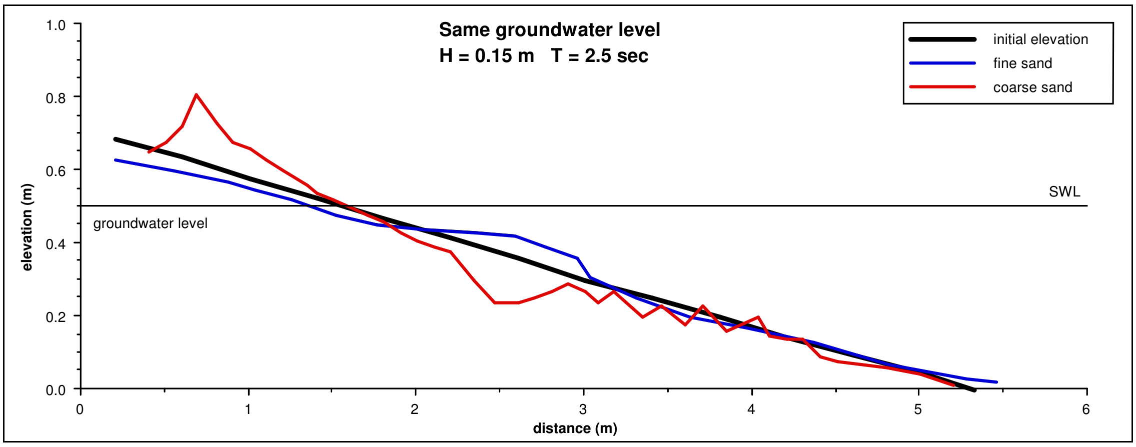


Figure 5.3 Comparison of fine and coarse sand profiles for swell conditions (T=2.5s, H=0.15m), inland groundwater level the same as SWL

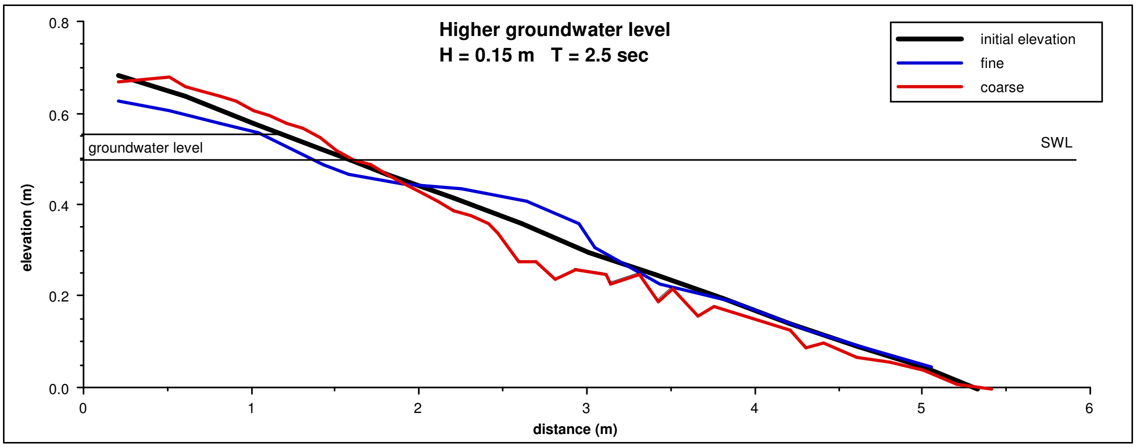


Figure 5.4 **Comparison of fine and coarse sand profiles for swell conditions (T=2.5s, H=0.15m), inland groundwater level above SWL**

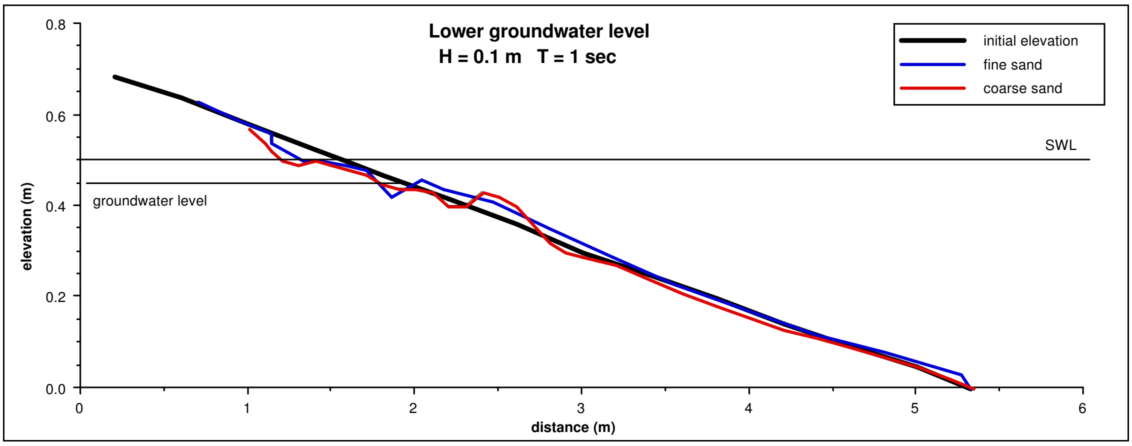


Figure 5.5 **Comparison of fine and coarse sand profiles for storm conditions (T=1s, H=0.1m), inland groundwater level below SWL**

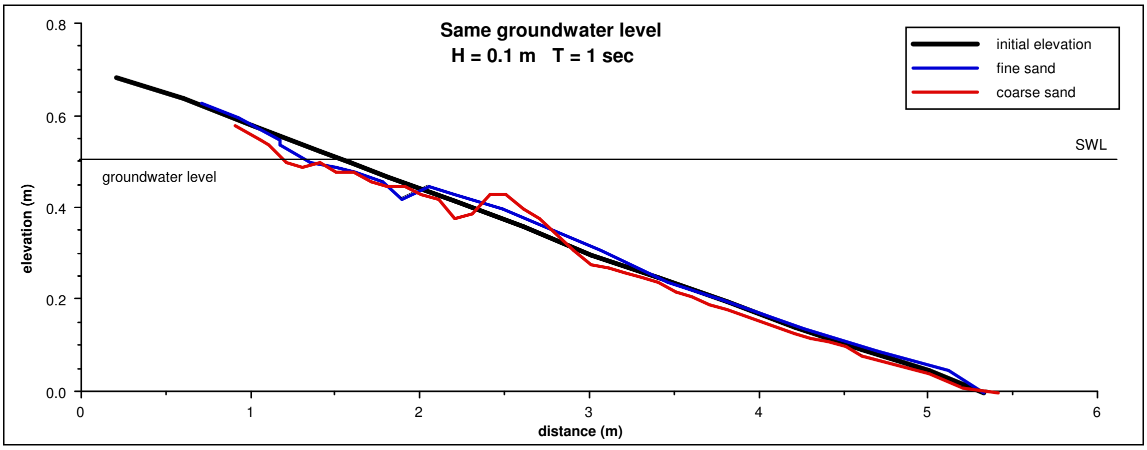


Figure 5.6 **Comparison of fine and coarse sand profiles for storm conditions (T=1s, H=0.1m), inland groundwater level the same as SWL**

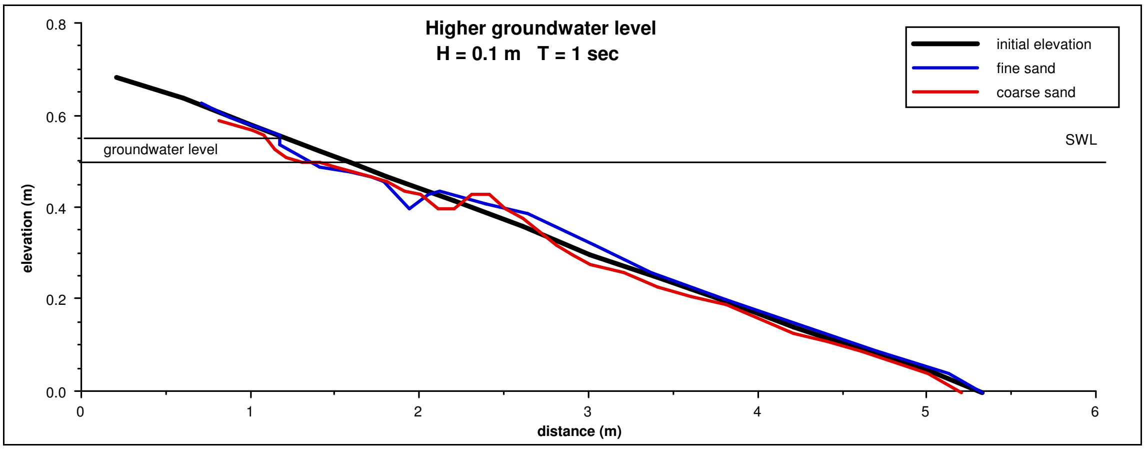


Figure 5.7. Comparison of fine and coarse sand profiles for storm conditions (T=1s, H=0.1m), inland groundwater level above SWL

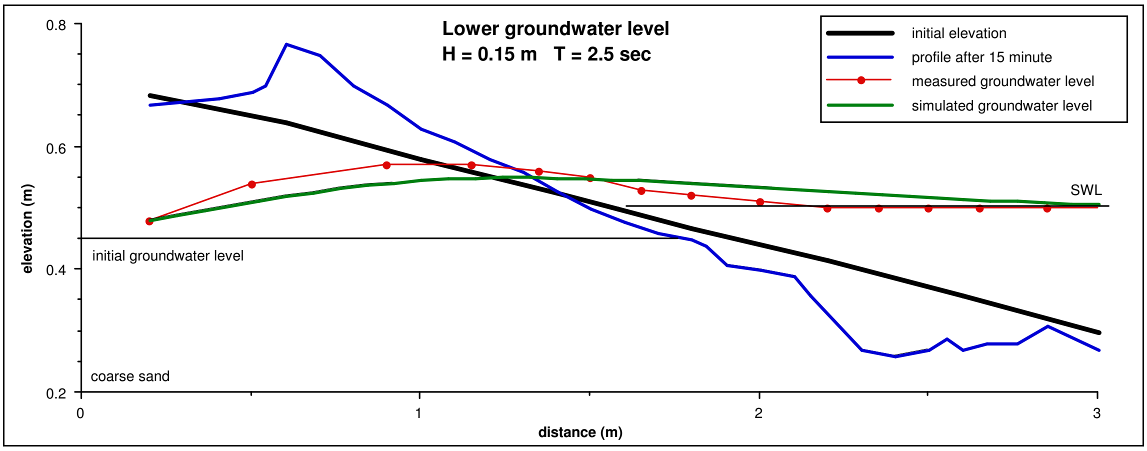


Figure 5.8 Measured versus modelled groundwater levels for swell conditions (T=2.5s, H=0.15m) on the coarse sand beach, inland groundwater level below SWL

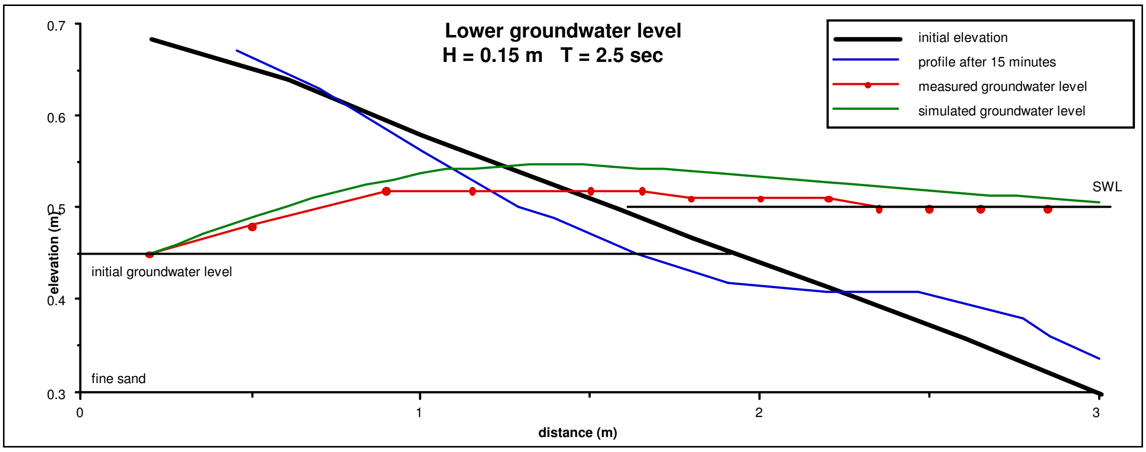


Figure 5.9 Measured versus modelled groundwater levels for swell conditions (T=2.5s, H=0.15m) on the fine sand beach, inland groundwater level below SWL

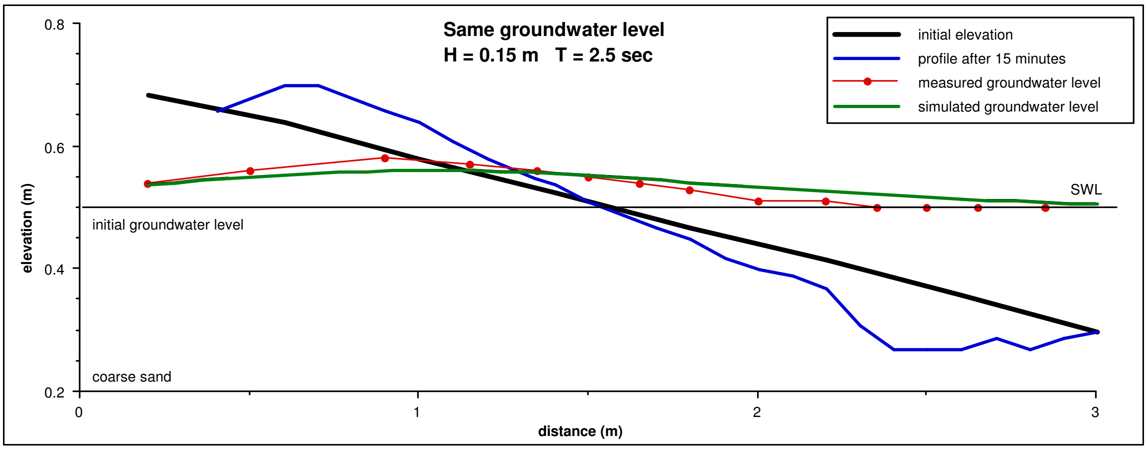


Figure 5.10 Measured versus modelled groundwater levels for swell conditions (T=2.5s, H=0.15m) on the coarse sand beach, inland groundwater level the same as SWL

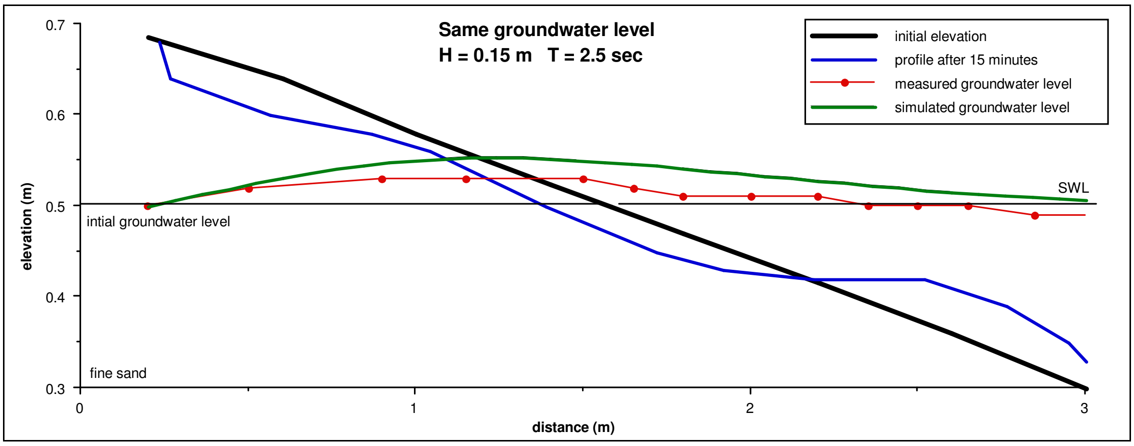


Figure 5.11 Measured versus modelled groundwater levels for swell conditions (T=2.5s, H=0.15m) on the fine sand beach, inland groundwater level the same as SWL

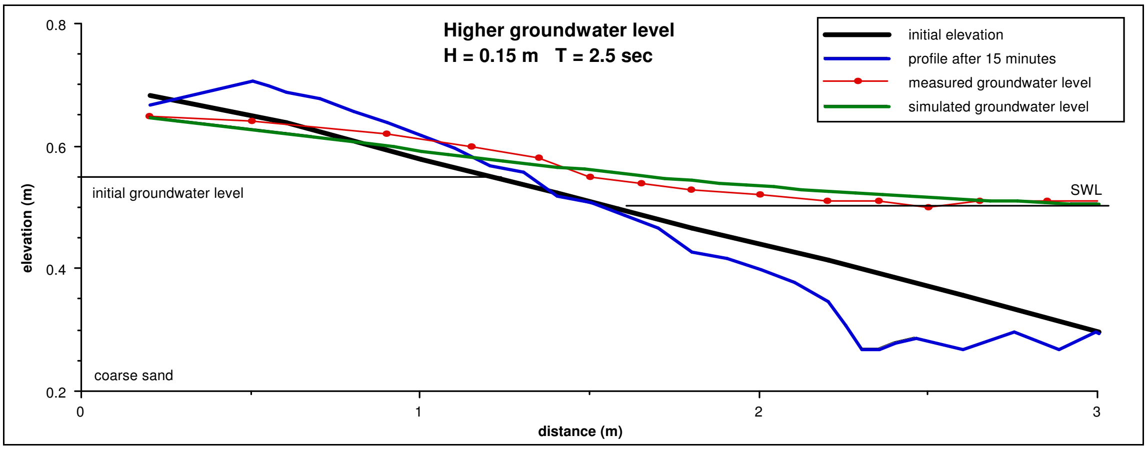


Figure 5.12 Measured versus modelled groundwater levels for swell conditions (T=2.5s, H=0.15m) on the coarse sand beach, inland groundwater level below SWL

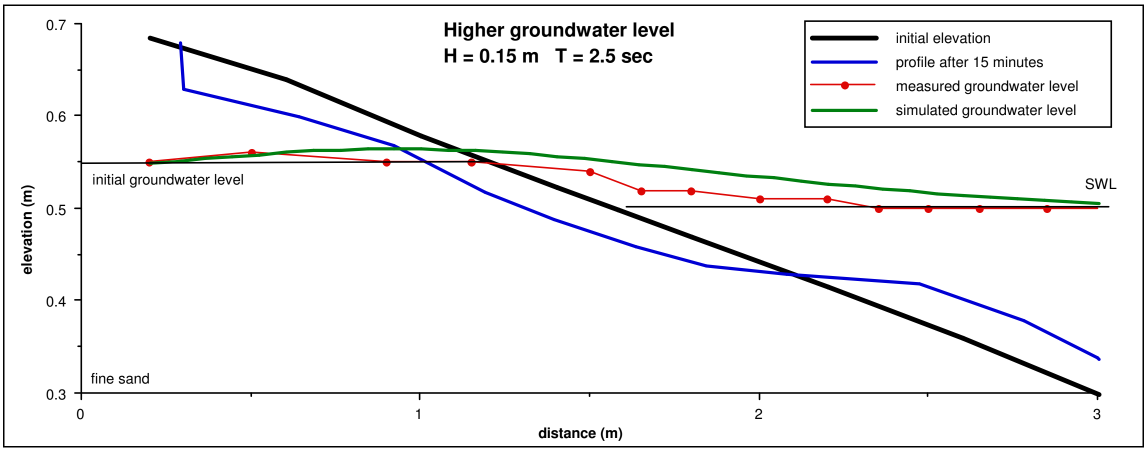


Figure 5.13 Measured versus modelled groundwater levels for swell conditions (T=2.5s, H=0.15m) on the fine sand beach, inland groundwater level below SWL

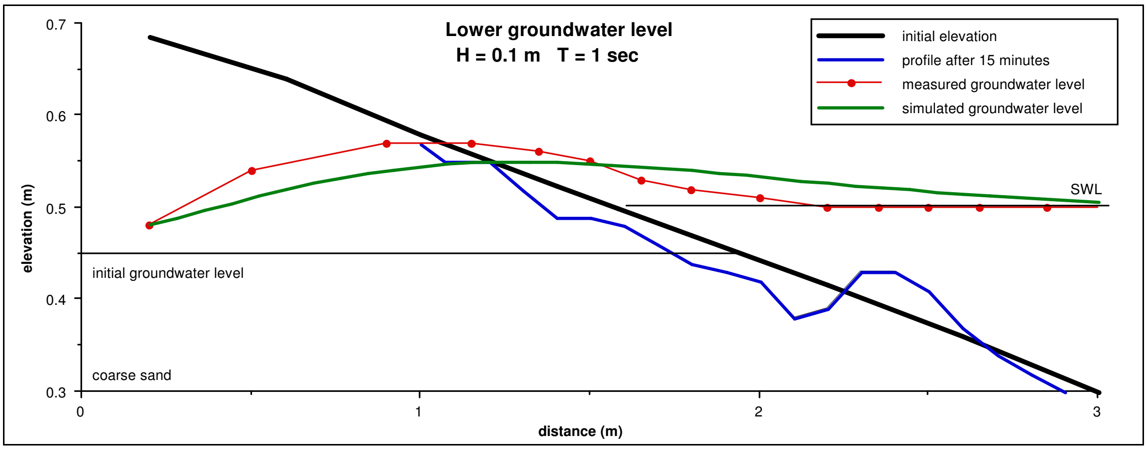


Figure 5.14 Measured versus modelled groundwater levels for storm conditions (T=1s, H=0.1m) on the coarse sand beach, inland groundwater level below SWL

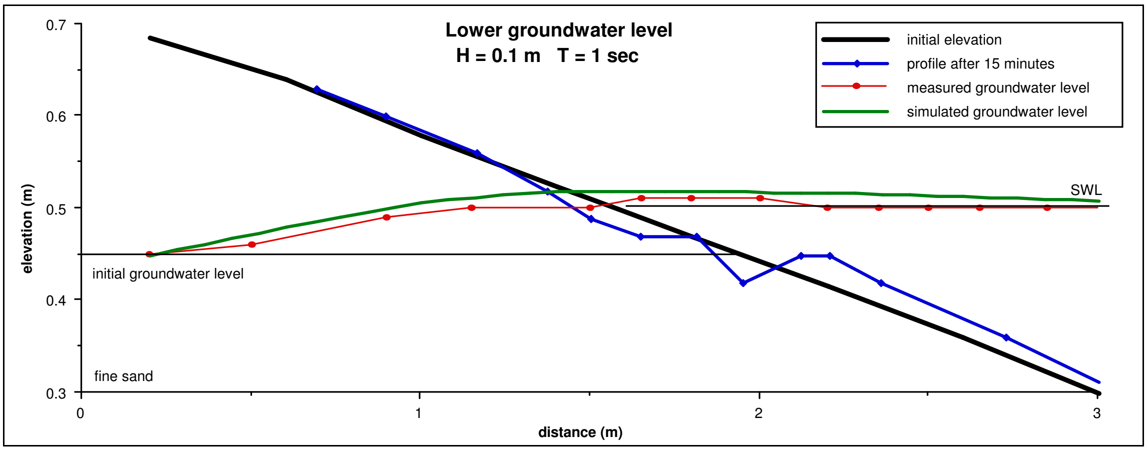


Figure 5.15 Measured versus modelled groundwater levels for storm conditions (T=1s, H=0.1m) on the fine sand beach, inland groundwater level below SWL

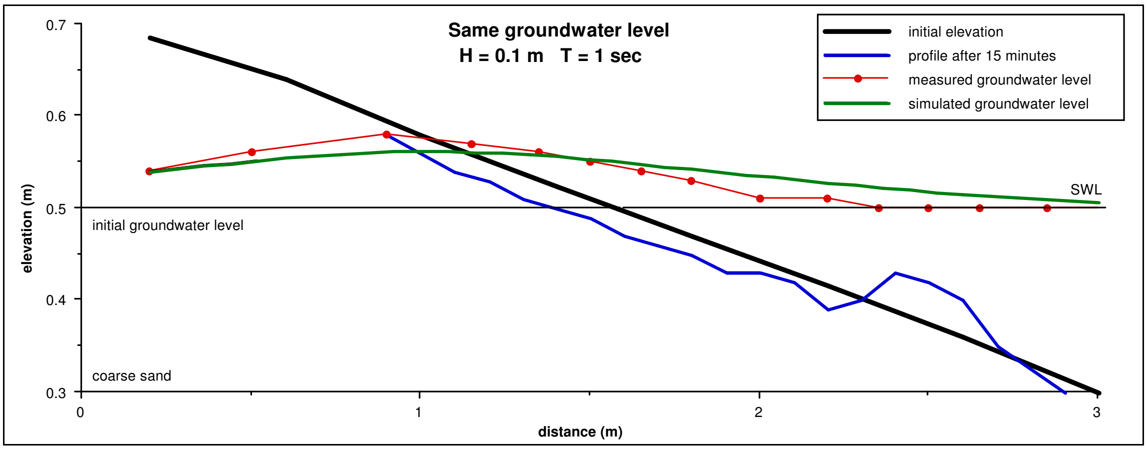


Figure 5.16 Measured versus modelled groundwater levels for storm conditions (T=1s, H=0.1m) on the coarse sand beach, inland groundwater level the same as SWL

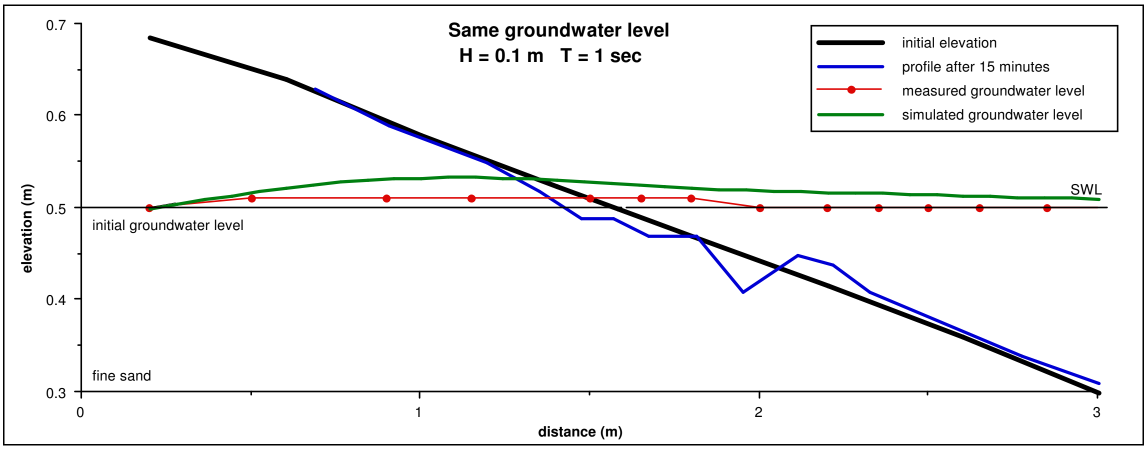


Figure 5.17 Measured versus modelled groundwater levels for storm conditions (T=1s, H=0.1m) on the fine sand beach, inland groundwater level the same as SWL

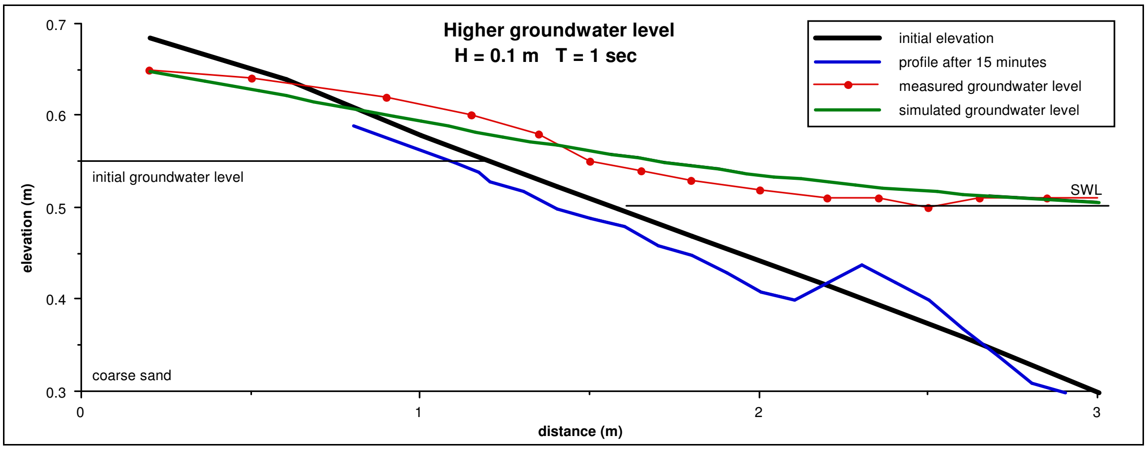


Figure 5.18 Measured versus modelled groundwater levels for storm conditions (T=1s, H=0.1m) on the coarse sand beach, inland groundwater level below SWL

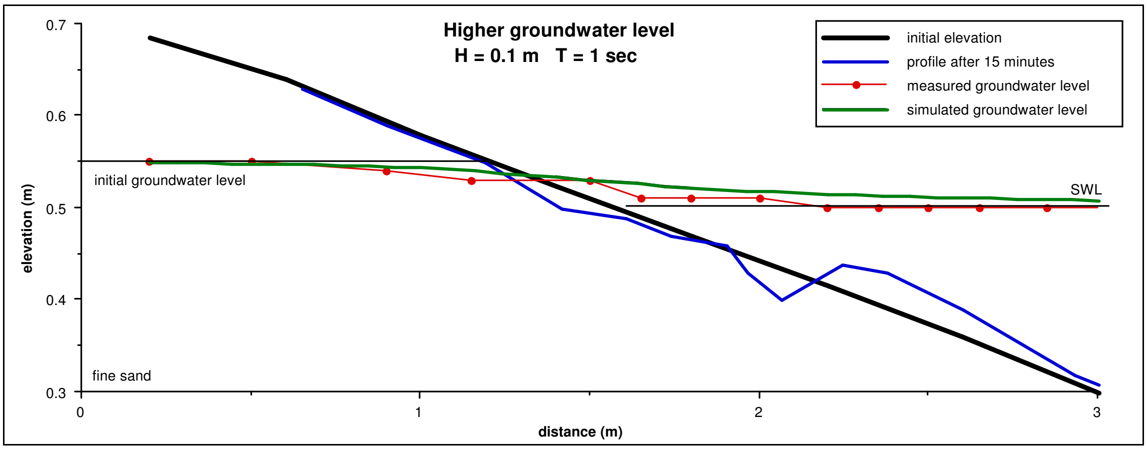


Figure 5.19 Measured versus modelled groundwater levels for storm conditions (T=1s, H=0.1m) on the fine sand beach, inland groundwater level below SWL

6. Case Studies

6.1 Introduction

The primary object in this part is to look at existing beach management practices in the UK, issues relating to dredging and placement methodologies, and available aggregate resources for mixed beaches. Two issues will be addressed. The first is concerned with the performance of recent beach recharge schemes; the second addresses alternative aggregate production, artificial placement, and management methods that may overcome problems associated with artificial mixing of beach sediment.

The case studies were led by the development and distribution of a questionnaire to gather information on shingle and mixed beach recharge schemes. The questionnaire was distributed to area offices of the Environment Agency (generally responsible for flood defence), maritime local authorities (generally responsible for coastal protection), and Coastal Group Chairmen, who facilitated further distribution of the questionnaire. Based on the questionnaire feedback, it was decided that the case studies should focus on three sites: Pevensey Bay in East Sussex, Eastoke Hayling Island in Hampshire and Tankerton Bay in Kent (Figure 6.1).

The detailed report on the case studies is included in Appendix 2 and the main findings are presented below.

Figure 6.1 Location of selected case studies

6.2 Performance Issues of Recharged Mixed Beaches

The case studies highlighted two 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. The second is cliffing, particularly in newly recharged beaches. 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 the bays with high sand fractions. This is significant, as the theoretical and laboratory investigations presented in Section 3 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 mix is at a minimum, and it has been observed that this results in a tendency for cliffing to occur. Figures 6.2 to 6.4 are examples of cliffing recorded at Pevensey Bay and Hayling Island.

Figure 6.2 Cliffing at Eastoke Hayling Island, photographed on 24/03/2004

Figure 6.3 Cliffing at Pevensey Bay, photographed on 02/07/2002

Figure 6.4 Cliffing at Pevensey Bay, photographed on 20/10/2005

The mechanism of cliffing is complicated. Both the theoretical analysis and field data show clearly that the high sand fraction is a major factor. Detailed records of beach profiles and wave climate at Hayling Island also suggest two other important factors. The first is the presence of sustained swell waves or storm waves of sufficient wave energy. The two severe cases of cliffing (where cliffs of ~1.7m height were formed) were both proceeded by recorded swell waves approaching 2m with dominant periods of 15s. At Pevensey Bay, cliffing was generally observed after storm attacks. The second factor seems to be 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 agreement with the recorded beach slopes found in the post-storm surveys along the Eastoke frontage (Figures 6.5 and 6.6).

A slope of around 1:7 is a commonly used design slope, which is chosen more for economic reasons than sound engineering. 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.

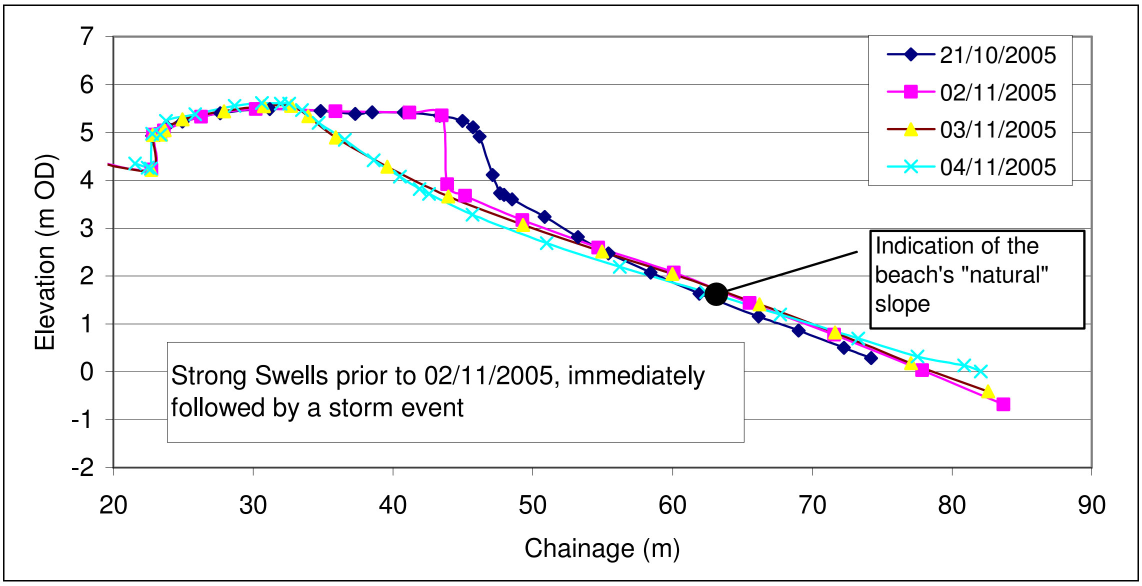


Figure 6.5 Profile evolution due to consecutive swell and storm action (Hayling Island)

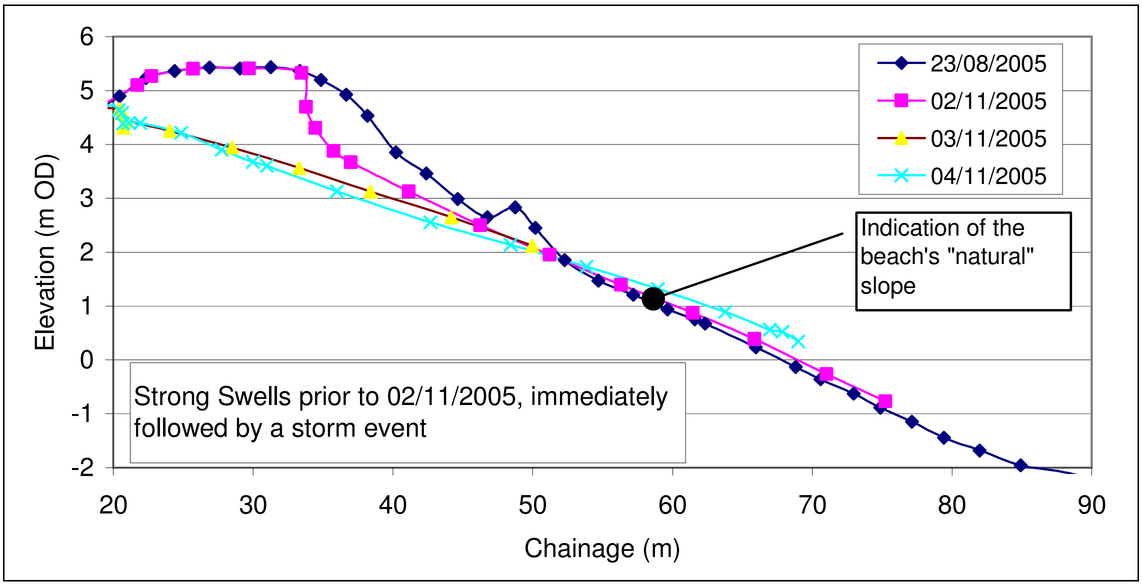


Figure 6.6 Profile evolution due to consecutive swell and storm action (Hayling Island)

6.3 Methods of Alleviating the Cliffing Problem

The theoretical study and field observations indicate that controlling the sand fraction of the sediment mix is a key to resolving the problem of cliffing. The three sites under study each experimented with a technique in dealing with the problem. The Tankerton approach was the use of a "cap" (top layer) of pure gravel (0.5~1m thickness) on top of the normal mixed sediment. The effect of capping on cliffing is clearly demonstrated by Figures 6.7 and 6.8.

Figure 6.7 Cliffing recorded at Tankerton site (45% Sand)

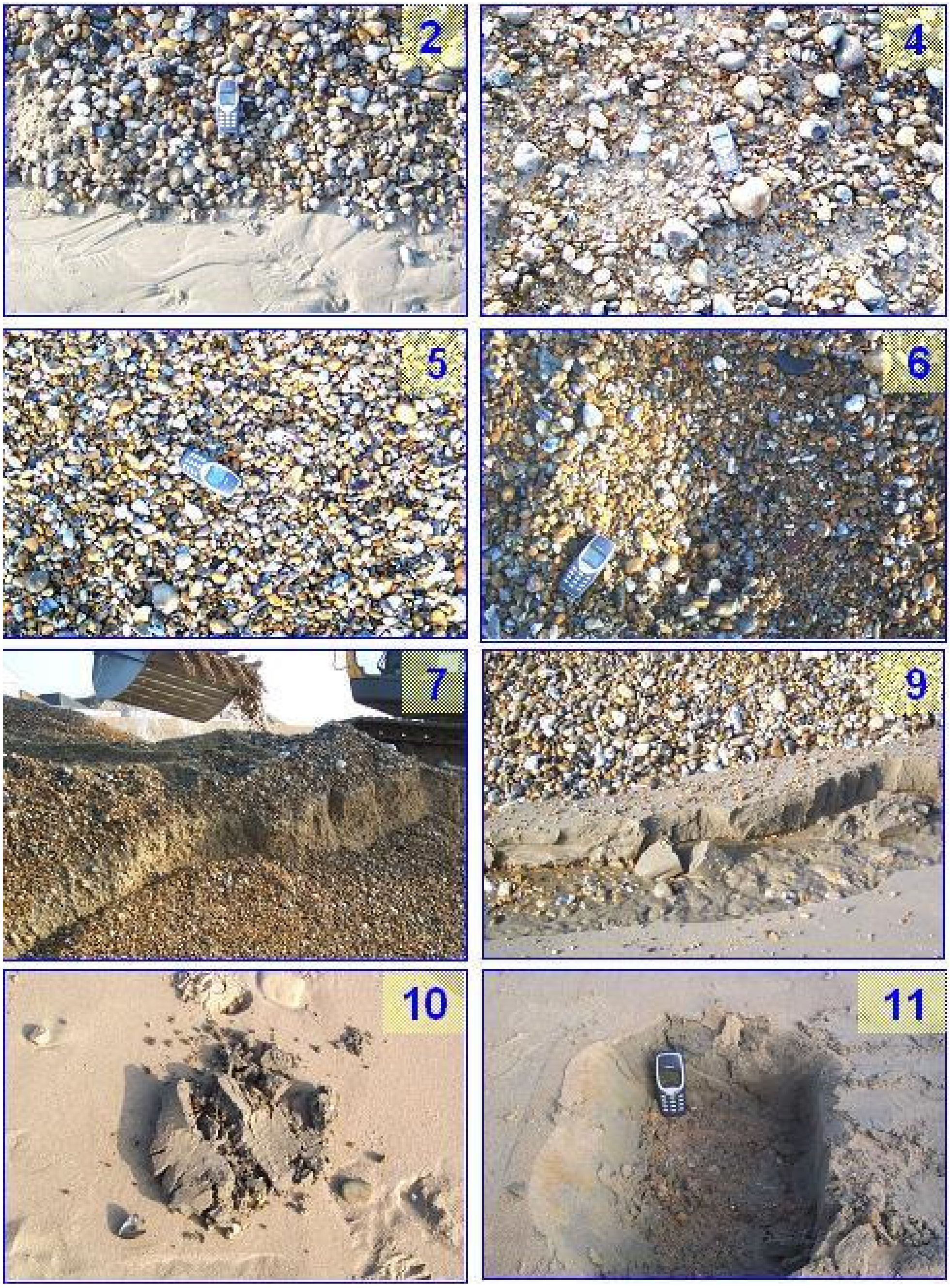
Figure 6.8 The state of the "capped" bay in contrast to that of Figure 6.7

The Hayling Island approach was similar to the Tankerton method but perhaps slightly more economical. In this case, the beach crest was recharged with recycled pure gravel. The method seemed very effective from the data collected so far.

While both the Tankerton and Hayling Island methods are effective, the widespread use of either method may prove difficult, due to limited availability of pure gravel resources. Field experiences indicate that offshore sediment resources contain isolated locations where pure or nearly pure gravel can be found. It is possible that the use of these gravel resources could be controlled so that they are used only for beach crest recharge. The controlled use will help the situation but it is unlikely that the natural gravel resources are enough for the need.

An alternative approach is that experimented with at Pevensey. In September 2001 the dredger Sospan Dau was introduced. This vessel not only collects the offshore sediment, but also discharges them directly on to the beach herself. As a converted barge she is able to come fully inshore at high water, and using a modified rainbowing technique, deposit the material in a discrete mound just in front of her bow. Dry plant is still required to recover the aggregate and place it to the required design, but because it is already substantially further up the beach only a bulldozer and excavator are necessary. Since September 2001 all recharge works have been undertaken using this modified rainbowing technique. The use of Sospan Dau has two clear advantages. The first is the reduced compaction due to less heavy plant operations, thus helping to alleviate the cliffing problem. Secondly, the modified rainbowing technique helps to segregate the fine sand from the coarser material. This can be demonstrated by Figures 6.9 to 6.12, showing the sediment grading during the September 2003 and September 2005 recharges. The separation of the material meant that the coarser sediment could be used in the crest section of the beach or the upper beach. The experience so far indicates that the method has great potential in significantly alleviating the cliffing problem. Importantly, the technique does not incur any additional cost.

Figure 6.9 Sediment mound and sample positions



Case Study Detail Pictures

2, 4, 5 & 6: Surface details

7 Typical Core detail

9, 10 & 11 Peripheral Details

Figure 6.10 Photographs of sediment at different positions of the mound.

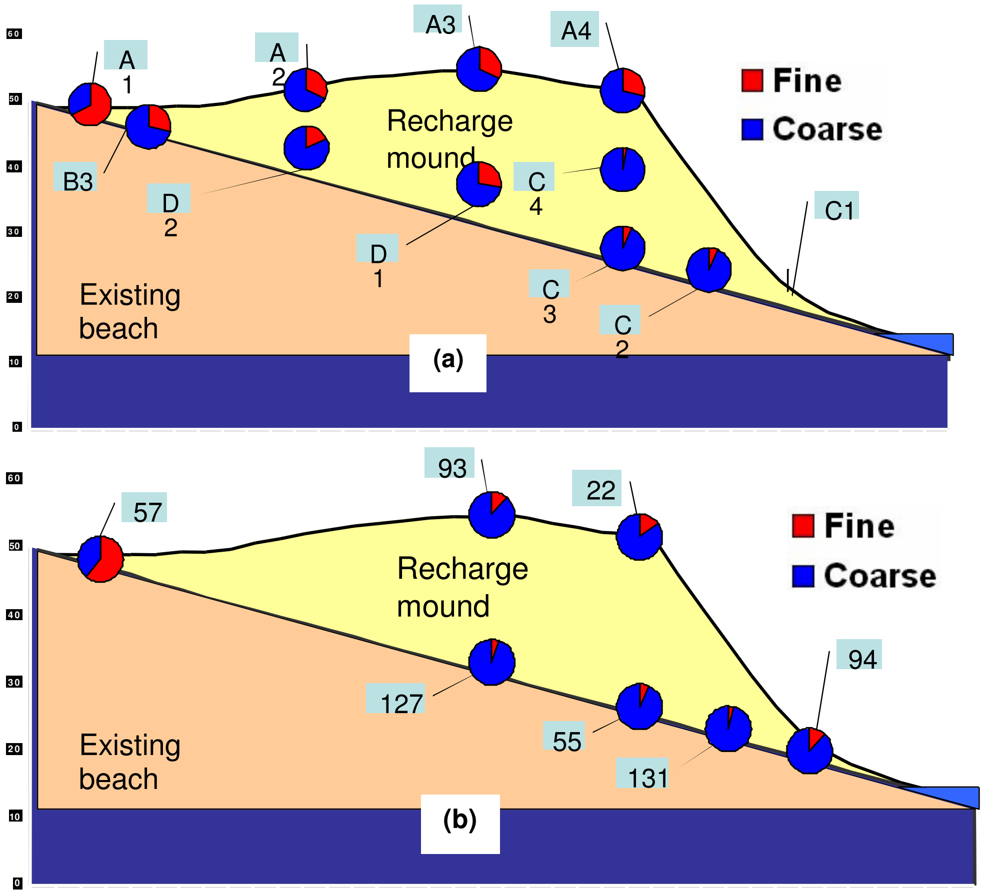


Figure 6.11 Cross-shore size variation (a: mound 1; b: mound 2)

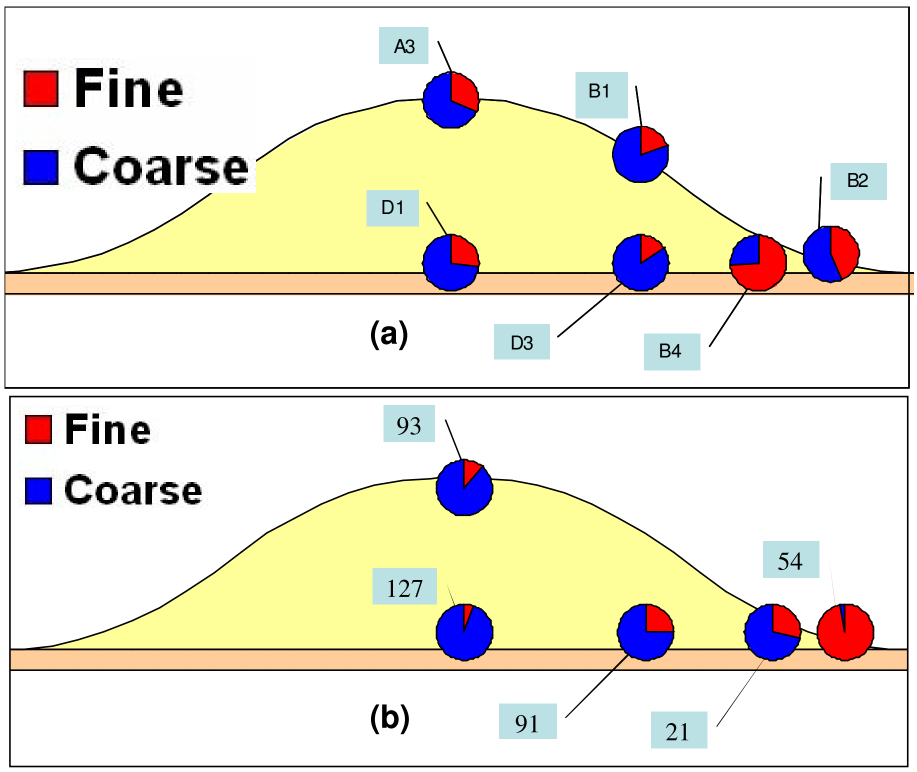


Figure 6.12 Longshore size variation in (a) mound 1 and (b) mound 2

6.4 Recycling of Material

In addition to major capital recharges, Pevensey Coastal Defence operates a policy of regular and frequent recycling operations on top of annual maintenance recharges. Figure 6.13 shows the cumulative quantity of the recharged material and recycled material. Note that there is a large step shown in the figure, which corresponds to the primary capital works between May 2002 and November 2002. A large volume of material was brought in to broaden the beach crest in order to achieve the required standard of defence. There are two points to be made in terms of maintenance recharge and recycling. The first is that the annual volume of the recycled material is relatively constant from year to year. The same may also be said about the annual volume of the maintenance recharge material. The second point is that the recycling involves a volume of material similar to that of the maintenance recharges. We can assume that the volume of the maintenance recharge material equates to the net loss of material from the beach. The recycling operations can be viewed as an effective means of maintaining the standard of defence while reducing the amount of imported material. In addition to effective use of sediment resources, the regular and frequent recycling operations are much cheaper to carry out than importing material from the sea.

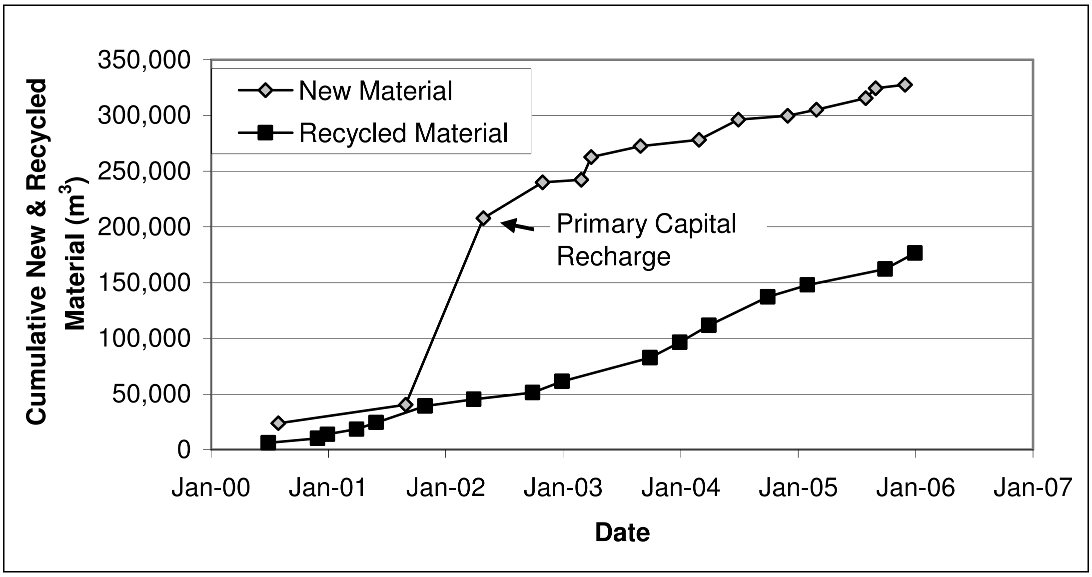


Figure 6.13 Cumulative new and recycled material

6.5 Summary

The case studies highlighted two significant problems of recharged mixed sand-gravel beaches: large loss of crest material and cliffing. Reinforcing the finding of the theoretical study, the case analysis showed that the cliffing problem is critically linked to the presence of a large sand percentage in the sediment mix. In addition, the beach face having a slope greater than the natural slope may also be an important factor leading to cliffing. Finally, cliffing can be a result of storm wave attacks but may also be caused by sustained swell waves of sufficient energy.

Controlling the sand percentage in the beach crest or the upper beach seems to be the key to alleviating the problem of cliffing. Managed use of limited gravel resources for recharging beach crests is one possible way forward, but this is unlikely to meet the practical needs. The modified rainbowing technique experimented with at Pevensey by PCDL offers a possible alternative that is both relatively effective and very economical.

Well managed recycling operations are an efficient use of sediment resources while offering significant cost savings.

7. Review of Aggregate Production, Placement and Mixing Methods

7.1 Introduction

The availability of sand and gravel aggregates, whether they are ‘won’ from land or sea, is a finite resource, and therefore needs to be used in an efficient and sustainable manner. Beach renourishment schemes represent a high specification use of aggregate resource, requiring relatively well defined sediment gradings to ensure adherence to the scheme design and acceptable beach performance.

7.2 Overview of Aggregate Dredging Techniques

Dredging for marine aggregates is now tightly controlled, with real-time monitoring of the dredger location as it moves over sand/gravel banks. The prevalent dredging technique used to collect sand and gravel deposits from the seabed is by trailing suction dredger, as confirmed by the three case studies reported herein. This works by dragging a suction pipeline from the dredger so that it just rests on the seabed. The movement of the dredger results in relatively thin layer of sediment being collected over a wide area, with minimal disturbance to the surrounding seabed. For sand and gravel banks where relatively thick deposits are present, anchored suction dredging can be used. In this method, the dredger is held in a constant position by an anchor, such that sand and gravel deposits at that location are collected; however, the seabed is more significantly disturbed, and lowered locally by up to 2m or more.

The cutter suction method employs a cutter head that describes an arc and disturbs sediment with the cutter head; this is subsequently passed up by suction through a pipeline to the dredger. Dredgers can either be stationary or move slowly to dredge sediment. Generally this results in lowering of the dredged area of the order of 0.1m, with modern instrumentation allowing relatively fine control of the cutter head.

7.3 Aggregate Placement and Mixing Techniques

Once sediment has been dredged from the seabed, a variety of methods are available to transport and place the material on the beach. These include:

- Placement of material directly from the dredger base, generally into the intertidal region (commonly referred to as the ‘split bottom’ method). This is a relatively simple method of placement, but requires significant further re-handling by heavy plant to move sediment into the desired location. In many cases the water is too shallow for the dredger itself to come to the beach, necessitating transhipment of the cargo to barges that then bring the sediment to the shore;

- Placement of material from the dredger pumped further onshore. This may result in material in the intertidal region, or further towards the upper beach (commonly referred to as the 'rainbow' method). This technique can result in reduced, or negligible, re-handling as material can be pumped to the required location to some extent;
- Placement of material from a pipeline attached to the dredger, pumping sediment onshore. This method is particularly used when a sediment source is available close by, to allow simultaneous dredging and pumping onshore. However, difficulties can arise with ensuring the stability of the pipeline if significant tidal currents are present. It is also cost-prohibitive for small recharge quantities;

In addition to this, more site specific techniques can be used, such as using a drag line to pull sediment back onshore from the nearshore (approximately up to 50m), or landing of sediment by barge, as used at Tankerton Bay.

A number of the placement techniques described above have been used in the three case studies. This allows some comparative assessment to be made between the effectiveness of different techniques, although the conditions at each site will necessarily be different.

Eastoke Hayling Island in particular has used two very different methods of placement: split bottom dumping and rainbowing. The split bottom capital recharge of 1985 was estimated to have an initial loss of 24%. This is comparable with the initial loss of 29% that occurred at Pevensey Bay during a similar split bottom recharge in 2000.

Later capital recharge events at both Eastoke Hayling Island and Pevensey Bay used the rainbow method, with losses that were generally lower than for the split bottom method, between 11 and 16%.

A significantly different placement technique has been applied at Tankerton Bay, where the recharge sediment has been transferred from a trailing suction dredger to a flat bottom barge that approached extremely close to the shoreline. The tipping of material from the front of the barge and placement further up the beach represented a more efficient use of recharge material.

However, the situation is complicated by the fact that the reduction in recharge sediment loss generally means that greater volumes of sand are retained initially throughout the beach, resulting in a beach profile response of upper beach cliffing and lower beach flattening.

Eastoke Hayling Island now also uses an intermediate technique, in that recharge sediment is sourced from the local Chichester Harbour approach channel. This provides a relatively cheap source of recharge sediment, which due to its source being Eastoke beach itself, provides good quality recharge material.

In conjunction with the different initial placement techniques, a variety of methods have been used to spread the recharge material subsequent to placement. At all the scheme sites, the recharge material is spread initially by heavy plant (although in using the rainbow technique this could be left as initially placed to be transported naturally, depending on the site).

Spreading of the recharge material is 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.

A new recovery technique was trialled at Pevensey in September 2003. It had been observed in previous recharges that in a typical deposition mound resulting from the Sospan Dau's modified rainbowing technique, the fine material tended to migrate furthest from the point of discharge, with the coarser sediment remaining in the centre of the mound. This feature forms the basis of the new recovery technique: rather than simply adding the unsorted sediment to the crest, only the coarse sediment in the core of the deposition mound was taken to the upper beach, leaving the sand at the periphery on the upper/ mid-foreshore. This technique should mean that less sand is placed on the beach crest, with less potential for cliffing.

An important lesson from the Pevensey experience is that recharge from offshore alone is not sufficient to maintain healthy beaches. Reprofiling the recharged beaches and frequent recycling of material from areas of accretion to areas of erosion help to maintain crest height and beach width and reduce the need for new material from offshore. This is particularly important in areas with significant longshore transport, as any additional sediment added to the beach simply increases the rate of longshore transport and therefore the loss of sediment from the site. Relatively small and frequent recycling to complement an annual recharge appears to be the most effective method of retaining the required beach volume.

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.

7.4 Existing and Potential Aggregate Resource

It has previously been summarised that demand for shingle recharge sediment is high, with anticipated requirements for shingle recharge sediment to 2015 estimated as up to 6.5M m^3/yr (Humphreys et al. 1996; Coates et al. 2001), although more recently a lower annual rate of around 2M m^3 has been suggested (Bellamy 2003).

A large amount of data is available on the production of aggregate within England and Wales, generally collected by the Crown Estate. Primary aggregate (previously unused) production statistics are relatively well documented, whereas secondary or recycled aggregate data is more sparse and less clearly defined. The availability and use of secondary and recycled aggregate is currently a significantly active area of research.

The primary aggregate resource is generally divided into land won and marine dredged aggregate. Further to this the aggregate resource is separated into sand and gravel, and crushed rock. The use of the available aggregate is sub-divided generally into 'aggregate' and 'non-aggregate' uses; the term 'aggregate' covers a variety of uses, but includes beach replenishment.

The general reporting method in the literature is to give all aggregate amounts in tonnes; for the purposes of this project, and to facilitate comparison with capital recharge volumes for beach replenishment schemes, all aggregate amounts are converted to volumes, applying a representative density of 1700 kg/m^3 (as recommended by the Crown Estate) but this may vary depending on the aggregate location of concern.

Overall Aggregate Resource

From the AM2001 Collation (BGS 2003), a total of 133M m^3 of primary aggregate (from land and marine sources) was sold throughout England and Wales in 2001, of which over 90% was quarried/landed in England. Of this, sand and gravel comprises 49.3M m^3 of this total (summarised from Table 7.1).

The general trend for sales of sand and gravel (land won and marine dredged, for all uses) has been variable since 1973 (ranging from 46M m^3 to 70M m^3), but since the 1990s has settled to a relatively stable average of approximately 47M m^3.

Table 7.1 Summary of primary aggregate (sand and gravel) sales

Region	Land won and marine dredged sand and gravel			
	Aggregate (Mt)	Non-aggregate (Mt)	Aggregate (Mm^3)	Non-aggregate (Mm^3)
South West	5.79	0.07	3.41	0.04
South East	19.67	0.85	11.57	0.50
London	4.56	0.00	2.68	0.00
East of England	16.41	0.49	9.65	0.29
East Midlands	10.05	0.21	5.91	0.12
West Midlands	9.93	0.37	5.84	0.22
North West	3.54	1.70	2.08	1.00
Yorkshire and the Humber	5.21	0.03	3.07	0.02
North East	2.16	0.00	1.27	0.00
South Wales	1.29	0.02	0.76	0.01
North Wales	1.39	0.06	0.82	0.03
Sub total	80.01	3.78	47.06	2.22
Total	83.79		49.28	

The annual resource for sand and gravel is highly dependent on legislative procedures, as well as physical availability. Production from quarries is tightly controlled via planning permissions, and the marine dredged resource is dependent on dredging companies successfully prospecting, and applying for licences to dredge (through the Government View procedure).

The regional splits of sand and gravel volumes are significant, as transport is a significant percentage of overall cost. Figure 7.1 (sourced from BMAPA) shows that the vast majority of sand and gravel from marine dredging is used on the south east and north east coasts of England. The total amount of sand and gravel used by England and Wales is sourced by 21% marine dredging and 79% land won (over the last 5 years). Of the marine dredged sand and gravel, 18% of this is used for fill and beach replenishment. Records indicate that beach replenishment is predominantly supplied by marine dredged sand and gravel. The following sections give a review of the resource specific to land and marine sourced sediment.

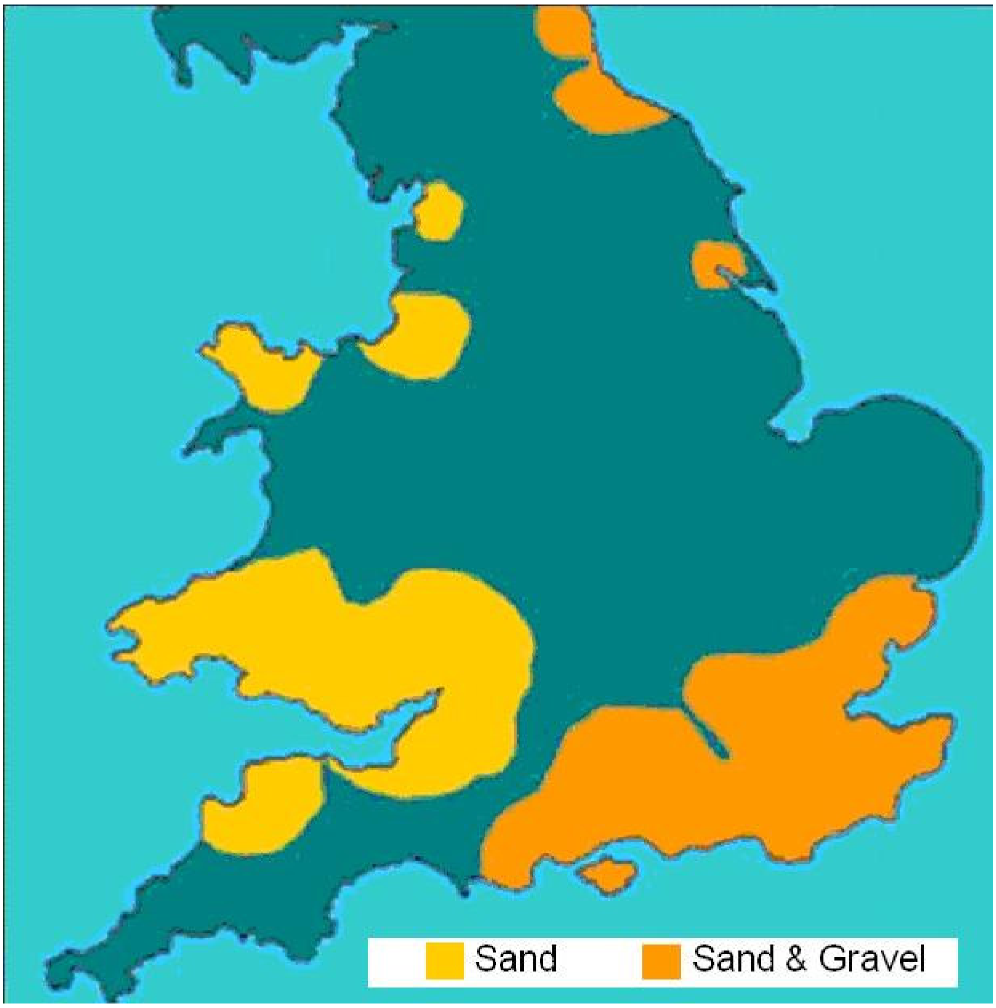


Figure 7.1 Map showing usage of marine dredged sand and gravel

Land Won Sand and Gravel

The production of land won aggregates is surveyed on a 4 yearly cycle by BGS, the latest published results being for the survey carried out in 2001 (and published by BGS in 2003).

The volumes of sand and gravel quarried between 1973 and 2003 in the UK are given in Table 7.2, collated from UK Minerals Yearbook (BGS 2004) and AM2001 (BGS 2003), with the permitted reserves included for comparison.

Table 7.2 Use of permitted reserve (1973 to 2003)

Year	Quarried sand and gravel (volume, Mm^3)	Permitted reserve of sand and gravel (volume, Mm^3)	Use of permitted reserve (%)
1973		683.53	
1983	53.65		
1984	53.29		
1985	53.76	511.76	10.5
1986	55.53		
1987	58.24		
1988	67.29		
1989	67.71	505.88	13.4
1990	60.59		
1991	52.53		
1992	48.24		
1993	49.24	544.12	9.1
1994	53.82		
1995	49.00		
1996	44.53		
1997	46.76	541.76	8.6
1998	46.06		
1999	47.24		
2000	47.06		
2001	47.53	460.59	10.3
2002	44.35		
2003	42.94		
Range	42 to 68	461 to 684	9 to 13

The trend for permitted reserves of land won sand and gravel (all uses) since 1973 has reduced from 683M m^3 to 461M m^3, with volumes generally decreasing in the 1990s. The permitted reserve in 2001 of 461M m^3 represents a 30 year low, although the amount of the permitted reserve actually quarried has generally remained around 8 to 10%.

The current permitted reserves (as defined in AM2001), for land won sand and gravel (for all uses) are given in Table 7.3, confirming the current total of 461M m^3.

Of significance is the distribution of permitted reserves: the two regions that have the largest reserves of sand and gravel are the East of England and the South East, which geographically compares favourably with the location of the majority of mixed beach replenishment schemes.

Table 7.3 Summary of permitted reserves of sand and gravel

Region	Permitted reserve of sand and gravel		
	Active sites (Mm^3)	Inactive sites (Mm^3)	Total (Mm^3)
South West	22.94	6.47	29.41
South East	72.35	10.59	83.53
London	1.76	0.00	1.76
East of England	90.00	18.82	108.82
East Midlands	46.47	11.76	58.24
West Midlands	67.65	17.06	84.71
North West	32.35	1.18	34.12
Yorkshire and the Humber	26.47	3.53	30.00
North East	7.65	4.71	12.35
South Wales	4.12	0.59	4.71
North Wales	11.76	1.76	13.53
Total	383.53	76.47	461.18

Marine Dredged Sand and Gravel

The current licensed dredge areas around or within Crown Estate ownership are shown in Figure 7.2, sourced from BMAPA. The production of marine dredged sand and gravel for beach replenishment purposes (sand, mixed, and gravel beaches) between 1983 and 2004 has been collated from BGS (2004) and Crown Estate (2004), and is shown graphically in Figure 7.3. The marine dredged sand and gravel volumes for all purposes are also included for comparison. Use of marine dredged sand and gravel peaked in 1996, both as an absolute volume and percentage of the dredged volume. Although between 1983 and 2003 the beach replenishment volumes varied from 0.5M m^3 to 4.1M m^3, in the last 5 years this appears to have settled to an annual volume of approximately 1M m^3. Previous estimates of beach replenishment demand have ranged from less than 2M m^3 (Bellamy, 2003) up to 6.5M m^3 (Humphreys et al. 1996); the volume estimated herein tends to support the more recent suggestion of Bellamy (2003).

From data given in Crown Estate (2004), all landings for beach replenishment in 2004 were for the South, East and Humber regions. The overall dredged sand and gravel volume represents approximately 53% of the permitted removal in licensed dredge sites (21.4M m^3 for 2004), with beach replenishment volumes approximately 4% of the permitted removal for 2004.

Figure 7.2 Licensed dredge areas in UK waters

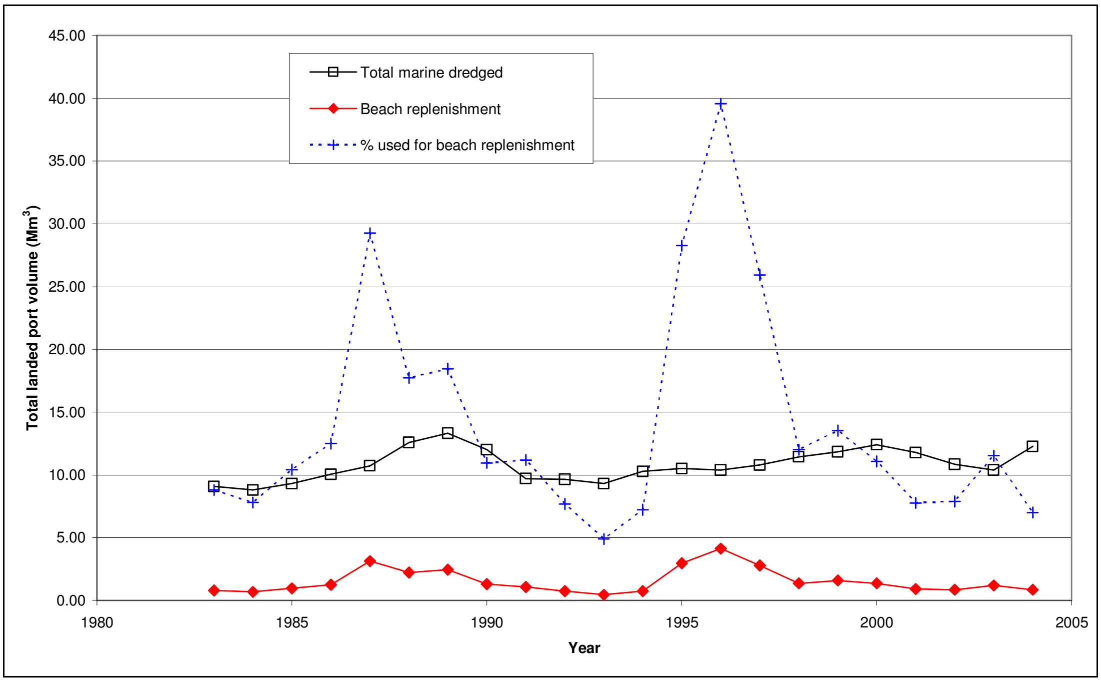


Figure 7.3 Variation in use of dredged sand and gravel for beach replenishment

The estimated reserves of sand and gravel are generally given in the literature (BMAPA 2001 to 2005) as licensed areas for dredging rather than tonnages. From these licensed dredge areas, contained active dredge areas are defined, with the area actually dredged by dredging companies only being a portion of this. It is apparent that the general trend is for licensed, active, and dredged areas to decrease over time. This reflects a variety of factors, including dredging technology improvements, allowing dredged areas to be more effectively used.

More detailed data on the volume of material dredged in relation to the permitted licensed amount for 2004 is given in Table 7.4.

Table 7.4 Regional volumes for dredged sand and gravel (2004)

Region	Permitted dredge volume (Mm^3)	Actual dredge volume (Mm^3)
Humber	2.74	1.90
East Coast	7.47	5.21
Thames	2.03	0.59
South	7.43	3.62
South West	1.51	0.96
North West	0.81	0.33
Total	21.99	12.62

Again, the geographical spread of landed dredged sand and gravel is comparable to the general location of mixed beach replenishment schemes, although this does not necessarily directly relate to increased dredging to supply beach replenishment schemes; the majority of dredged sand and gravel is used for other purposes.

A significant increase in available area for dredging sand and gravel is currently being considered, due to the discovery of significant sand and gravel deposits in the eastern English Channel. The actual extent of dredge, and whether it will be accepted, is still undergoing study, but the proposed maximum dredging area is estimated to be 117 km^2 over 15 years.

The remaining resource available for beach replenishment schemes is dependent on the specification of the required sediment; tightly specified sediment gradings would obviously restrict the acceptable dredged sediment volume. A summary of the available resources for mixed beach schemes on the UK south coast (HR Wallingford 2004) indicates that the available resource for 2004 was significantly in excess of 2M m^3. However, further data is required to estimate the total available resource (in particular for mixed beaches) from the existing licensed dredge sites.

Summary

The above discussion has described the historic and present sand and gravel resources from both quarrying and marine dredging. A summary of the relative production volumes of sand and gravel from marine and land sources (and relative percentage of the total) is given in Table 7.5. It is apparent that sand and gravel in general is predominantly sourced from land quarries. However, the trend over the last 20 years has been for marine dredged volumes to increase from 15% to 20% of the production total.

It has previously been suggested (Bellamy 2003) that the existing physical resource of marine sand and gravel is sufficient for beach replenishment schemes (for all beach types) for a number of decades, although it was noted that licenses for extraction represent a possible limit. Considering that the use of marine dredged sand and gravel for beach replenishment schemes in the last 5 years has been less than 12% of the total, this suggestion does not seem unreasonable. However, the design requirement for mixed beach capital recharge material to have a significant coarse fraction may well limit the availability of sediment with acceptable grading. A possible solution to this would be to source further material from land quarries to artificially increase the volume of coarse material in the beach.

Table 7.5 Relative volumes of land won and marine dredged sand and gravel

Year	Sand and gravel (volume, Mm^3)		
	Land won	Marine dredged	Total
1983	53.65 (85%)	9.35 (15%)	63.00
1984	53.29 (85%)	9.06 (15%)	62.35
1985	53.76 (85%)	9.59 (15%)	63.35
1986	55.53 (84%)	10.35 (16%)	65.88
1987	58.24 (84%)	11.06 (16%)	69.29
1988	67.29 (84%)	12.94 (16%)	80.24
1989	67.71 (83%)	13.71 (17%)	81.41
1990	60.59 (83%)	12.35 (17%)	72.94
1991	52.53 (84%)	10.00 (16%)	62.53
1992	48.24 (83%)	9.94 (17%)	58.18
1993	49.24 (84%)	9.59 (16%)	58.82
1994	53.82 (84%)	10.59 (16%)	64.41
1995	49.00 (82%)	10.82 (18%)	59.82
1996	44.53 (81%)	10.71 (19%)	55.24
1997	46.76 (81%)	11.12 (19%)	57.88
1998	46.06 (80%)	11.76 (20%)	57.82
1999	47.24 (80%)	12.18 (20%)	59.41
2000	47.06 (79%)	12.76 (21%)	59.82
2001	47.53 (80%)	12.12 (20%)	59.65
2002	44.35 (80%)	11.18 (20%)	55.53
2003	42.94 (80%)	10.71 (20%)	53.65
Range	42 to 68	8.8 to 13.3	53 to 81

8. Conclusions and Recommendations

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 ambiguity in the literature, with the term “shingle” being used to describe both pure gravel and mixed sand and gravel beaches. It is preferable to distinguish between gravel beaches and mixed sand-gravel beaches rather than use the term “shingle 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 that 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 dominantly 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 head material in storm events. Both problems seem to be closely linked to the presence of a relatively large sand fraction, and also to 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. 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 of the quality over 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 underlay of normal mixed sand-gravel material. The Hayling Island frontage also experimented with the beach head being constructed with recycled gravel and at Pevensey Bay a new sediment spreading technique has being tried out. It is recommended that such field experiments should continue but

additional support should be given so that continuous monitoring can be carried out. 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.

- To quantify the available resource of sand and gravel, collection of data on the total physical amount from licensed sites, and the grading characteristics of the aggregate would be required. Additionally, data on the planned future capital recharge requirement for existing and proposed schemes would also be needed, to clearly indicate the remaining life of the physical resource.

- Groundwater monitoring such as that carried out at the Tankerton site should continue. If this is not possible at this site, alternative locations should be sought. The internal flow of a recharged mixed sand-gravel beach needs better understanding to help search for better methods that may improve the beach performance. Such field monitoring should be carried out in conjunction with detailed numerical modelling.

- A standard methodology is required to characterise bimodal sediment distributions and sediment size variation on mixed beaches. The existing knowledge in relation to unidirectional flow may be a good starting point of development for mixed sediments under oscillatory flow. Detailed measurements of sediment size distributions on mixed beaches, including sand content, should be carried out in order to determine the natural amount of spatial and temporal variability. The effect of sampling methodology should be considered as part of this measurement programme.

- Detailed laboratory permeameter measurements of hydraulic conductivity in different sediment mixtures should be carried out with a range of sand and gravel sizes and different proportions of sand and gravel. It is important to test current assumptions about the effect of increasing sand content, as these are based on a limited number of laboratory experiments with only one, relatively small, gravel size.

- Laboratory experiments on initiation of motion in mixed sediments should be carried out with a range of sand and gravel sizes and different proportions of sand and gravel. The effect of adding sand to gravel and gravel to sand should be investigated. These experiments should also be carried out with poorly sorted gravels and sands in different mixtures.

- Laboratory experiments on sediment transport and beach profile evolution in mixed sediments should be carried out with a range of sand and gravel sizes and different proportions of sand and gravel. The effect of adding both sand to gravel and gravel to sand should be investigated. Attempts should be made to establish the exact role of hydraulic conductivity in the variability of the beach profile evolution.

- Laboratory and field measurements of infiltration/ exfiltration and hydraulic gradients in mixed beaches, and a range of sediment mixtures, are urgently required. These measurements should include concurrent measurements of hydraulic conductivity, watertable elevation and moisture content.

- Predictions of existing models must be tested against data from mixed sand and gravel beaches. In particular, model simulations of the effects of infiltration and changes in hydraulic conductivity should be validated against laboratory/field data.
- Study of natural beaches in relation to the cliffing phenomenon and distribution of particle sizes should help in identifying ways of dealing with the cliffing problem and improving the material placement strategies.
- The sorting of sediment following a beach recharge should be monitored. This will help improve the material spreading strategies to minimise possible negative impact of sediment sorting on the beach performance.

Table 8.1 summarises the recommendations in terms of types of work/study and relevant groups of interest, with priorities of the recommended work 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 • experiments on the effect of sand fraction and other factors on cliffing • experiments on the optimum design profile to reduce cliffing • experiments on sediment transport and beach profile evolution using a range of sediment mixtures, with concurrent measurements of hydraulic conductivity • experiments on effects of compaction	• permeameter measurements of hydraulic conductivity with a range of sediment mixtures • experiments on initiation of motion using a range of sediment mixtures • experiments on initiation of motion, sediment transport and beach profile evolution with infiltration/exfiltration • experiments on kinetic sorting using a range of sediment mixtures • experiments on reflection on mixed beaches • 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 • experiments on placement of coarse material on upper beach • measurements of adjacent sites with normally placed and selectively placed recharge material • 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 • short-term tracer experiment to identify sediment transport paths on recharged beaches • Cliffing and sediment size distribution of natural 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 • Monitor sediment sorting following a recharge • 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 • collect data on total amount of sand and gravel available from licensed sites • collect data on future capital recharge programmes for existing schemes to define remaining life of currently licensed resource • 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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