DEPARTMENT for ENVIRONMENT, FOOD and RURAL AFFAIRS

Research and Development

Final Project Report

(Not to be used for LINK projects)

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Project title	Development of predictive tools and design guidance for mixed beaches - Stage 2
DEFRA project code	**FD1901**
Contractor organisation and location	HR Wallingford Ltd, Wallingford, Oxon
Total DEFRA project costs	£ £400,000
Project start date	01/04/00
Project end date	31/03/03

Executive summary (maximum 2 sides A4)

The overall aim of the research was to facilitate the development of Coastal Strategy Plans and Beach Management Plans by:

- Improving understanding of processes and responses for beaches with widely graded sediments including sand and gravel
- Developing predictive tools for beach responses
- Disseminating information and guidance to UK shoreline managers.

The objectives of this programme were to:

- Consolidate MAFF funded work on surf zone hydrodynamic over porous beaches (OTTP – ANEMONE and Shingle Beach Research Programmes)
- Continue to monitor and review existing data, published research, laboratory studies and numerical model developments both in the UK and internationally
- Undertake process studies of the important factors controlling transport (threshold of motion, flows through porous sediment) using physical models
- Develop a conceptual model of cross-shore transport into a numerical study
- Disseminate guidance to the UK and EU coastal community

The following work has been completed over the three years:
First year:

- Literature review on mixed beach and graded sediment processes
- Characterisation of UK mixed beaches
- Field experiment at Seaford
- Permeameter and preliminary threshold experiments
- Preliminary swash zone velocity experiments

Second year:

- Further development and validation of the OTTP cross-shore beach model

- Field experiment at Slapton Sands
- Completion of boundary layer experiments using small scale flume facilities
- Further literature review on experimental research
- Detailed planning, team meetings, training and start-up of EU-TMR full scale wave flume research using the GWK facility in Hannover, working with a project team from UK and European Universities.
- Preparation and presentation of a conference paper and a journal paper

Third year:

- Successful completion of the GWK experiments, with compilation of all experimental data for use by other researchers within Report TR130
- Presentation of two conference papers at ICCE 2002
- Submission of a paper for Defra 2003
- Presentation of several workshop papers at EU research meetings
- Preparation of the final technical report.

In addition, the project has provided training and research opportunities for a number of young scientists, and has fostered collaborations between HR Wallingford and UK, French, Italian and German Universities. These collaborations realised a very high return through access to academic research, field measurement programmes, laboratory facilities and, most importantly, the opportunity to undertake unique prototype scale experiments within the EU funded GWK facility in Hannover. The final project report draws extensively on the HR Wallingford sponsored PhD thesis submitted by Lopez de San Roman Blanco (2003) that provides a full and detailed account of most of the research associated with this project.

Scientific report (maximum 20 sides A4)

1 INTRODUCTION

HR Wallingford was commissioned by Defra to undertake a 3-year project on the research and development of predictive tools and the application of these tools and knowledge in the management of mixed beaches. Mixed beaches are defined as those including both sand and coarser material, with sediment sizes ranging over as much as four orders of magnitude from fine sand (100μm), through gravel (2-64m) up to small boulders (>256mm) (Coates and Damgaard, 1999). Beaches of this type are found along much of the UK coastline, and in many other areas of the world.

This project was completed in March 2003. The aims of this research project were threefold:
- Improving understanding of processes and responses for beaches with widely graded sediments
- Developing predictive tools for beach responses
- Disseminating information and knowledge to UK shoreline managers.

The specific tasks in the proposal were:
- Consolidate recent MAFF (now Defra) funded work on surf zone hydrodynamic over porous beaches (for example the OTTP – ANEMONE (Dodd, 1998)) and Shingle Beach Research Programmes (Coates *et al.*, 1999)
- Continue to monitor and review existing data, published research, laboratory studies and numerical model developments both in the UK and internationally
- Undertake process studies of the important factors controlling transport using physical models
- Develop a conceptual model of beach processes influencing cross-shore sediment transport
- Disseminate information and knowledge to the UK and EU coastal community.

These specific tasks have been completed and the aims have been successfully achieved, laying the foundation for further research to develop more robust predictive methods applicable to a greater range of situations.

In addition, the project has provided training and research opportunities for a number of young scientists, and has fostered collaborations between HR Wallingford and UK, French, Italian and German Universities. These collaborations realised a very high return through access to academic research, field measurement programmes, laboratory facilities and, most importantly, the opportunity to undertake unique prototype scale experiments within the EU funded GWK facility in Hannover. This final project report draws extensively on the HR Wallingford sponsored PhD thesis submitted by Lopez de San Roman Blanco (2003) that provides a full and detailed account of most of the research associated with this project.

2 BACKGROUND

Coarse grained beaches are an important feature of the UK coastline. They form barrier beaches in front of low lying marsh lands, toe protection along eroding cliffs and wide, prograding nesses where local hydrodynamic conditions encourage deposition. These beaches are occasionally formed predominantly of steeply inclined gravel or cobbles, but more often they comprise a less steep upper beach of mixed sand and gravel fronted by a wide lower foreshore of sand or a rock platform. Although found in many other areas of the world, mixed beaches are of particular interest to UK shoreline managers where their coast defence characteristics help to protect substantial urban areas and high value agricultural, recreational and environmental assets.

From a coastal processes perspective mixed beaches are distinctly different to sand or gravel beaches, but with characteristics from both forms. By definition sand beaches comprise non-cohesive sediment between about 63μm and 2mm. Although the sand is permeable, the interstices in the swash zone are rapidly saturated leaving an essentially impermeable surface. Beach slopes range from about 1:100 to 1:12 between the highest point of wave run-up and the depth below which wave action causes no significant sediment transport. Throughout this zone sand can be transported by both waves and tidal currents, either as bedload or in suspension. Strong 3-dimensional forms, such as longshore bar and trough systems or cross-shore channels, are typical of sand beaches affected by combined waves and tides.

True gravel beaches are formed of material greater than 2mm, and may sometimes be dominated by much larger material up to cobbles (64mm – 256mm). The gravel is very permeable and tends to be sorted by size across shore, with large material thrown up to form a steep storm crest, with slopes typically ranging from 1:5 to 1:2. Transport is heavily dominated by wave action, with some material only mobile during storms. Homogeneous gravel beaches are rare except along rocky coasts where they frequently form pocket beaches. However, gravel beaches formed as storm ridges above a sand beach are more common, and tend to grade into the form commonly referred to as shingle beaches. For clarity of definition this report does not use the all-encompassing term “shingle”, and makes a clear distinction between gravel and mixed sand/gravel beaches.

Mixed beaches make up the intervening beach form between sand and gravel, comprising a mixture of grain sizes including sand and gravel, and sometimes cobbles. In common with all beach forms, there is often a significant component of shell fragments, typically in the size range of 1mm – 5mm. The distribution of the mixed beach material may vary across shore, along shore, vertically through the beach and over time (both seasonally and over longer time scales). The sand and gravel may be mixed below the surface, leaving the visible part as gravel, with a coarsening of material towards the beach crest. The larger interstitial spaces within this surface layer cause asymmetric onshore-offshore surface currents (some of the swash infiltrates the beachface rather than flowing down the beach surface as backwash). The result is onshore transport of the coarse material, until there is an equilibrium between the wave induced onshore forces and the down slope forces acting on the steep upper slope. Mixed beach slopes are typically around 1:6 - 1:12, often running down to a much flatter low tide or nearshore sand platform. Near the crest they may steepen to as much as 1:2, where they are essentially the same as a gravel ridge.

Transport of the gravel is primarily as bed load driven by wave action in the surf and swash zones, while the sand may also be influenced by non-wave induced currents, being carried as both suspended and bed load. During storms coarse material may be lifted into temporary suspension, and can, for example, be carried over groynes or up on to sea walls. Wave action alone will not normally cause gravel to be drawn seaward across typical low tide sand platforms, so the content of the beach may change as sand is drawn down by storms or returned shoreward by lower swell waves. Tidal currents can be locally significant, particularly off headlands or at estuary mouths where sand and gravel can be transported inshore or offshore, along with sand, to form substantial ebb or flood delta banks. These transport mechanisms can lead to complex littoral drift regimes, with different sediment sizes moving at different rates and even in different directions. Beach management and design of control structures need to consider this complexity to achieve long term success.

Coarse beach sediments are derived from a number of sources. In the recent geological past the major sources for most of the UK were glacial till and post-glacial river deposits along the coast and across the nearshore zone. These deposits were eroded and reworked into beach deposits as sea level rose after the last ice age. In addition much of the south-east coast and parts of the Norfolk coast have benefited from the post-glacial erosion of chalk cliffs releasing large volumes of embedded flint to the beaches. Since sea level stabilised at approximately its present level some 5000 years ago the nearshore and fluvial sources have gradually been depleted and are no longer feeding large quantities of gravel to the coast, except in mountainous areas of north-west Wales and Scotland. Erosion of soft cliffs now provides the main source of natural sediment input to the littoral system, supplemented in the last few decades by large scale beach nourishment schemes using marine dredged aggregate.

Although some gravel and mixed beaches are pro-grading (e.g. Orfordness, Dungeness) the more general trend is one of long term erosion. The normal cause of erosion is an imbalance between updrift inputs and downdrift or offshore transport. The reasons for this are diverse, and may include:

- natural depletion of sediment sources
- erosion of the nearshore zone or natural changes to nearshore bank morphology resulting in larger and more oblique waves reaching the beach
- construction of harbour breakwaters or other cross-shore structures that cut off longshore drift
- dredging of navigation channels or aggregate deposits
- protection of eroding cliffs that provide beach material
- climate variation resulting in changing wave directions or increased storminess.

Whatever the reason, the result is coastal erosion and/or an increased risk of flooding to adjacent low lying land. In the absence of human interests this would not be a problem: cliff erosion would feed new sediment into the littoral system and any flooding would maintain the saline character of backshore marshes. However, as human interests tend to dominate our perception of the shoreline, erosion and flooding are usually not welcomed.

The understanding of mixed sand/gravel beaches is relevant to the management of over one third of the shoreline of England and Wales, and almost all of the heavily populated south-east coast of England. However, despite their importance, the majority of the existing research into coastal processes and morphology change in the last fifty years has been concerned with sandy beaches. Some research has been devoted to gravel beaches and but almost none to mixed beaches, with some key issues having not been tackled at all (Mason and Coates, 2001).

Research into short-medium term (hours to years) coarse grained beach processes and management has been largely centred in the UK, although important work has been undertaken in New Zealand, Holland, Canada, Ireland, France, Japan and Denmark. Much of the UK work has been carried out through MAFF (now Defra) funded projects at HR Wallingford over the past two decades. This has included physical modelling of fundamental processes and beach-structure interactions, field monitoring of natural and recharged beaches, reviews of operational practices around the UK and development of parametric and morphodynamic numerical models. The *Beach Management Manual* (CIRIA, 1996) made use of much of this work. More recent work leading up to the present research includes the 1996-99 field measurement programme known as the Collaborative Shingle Beach Project (Coates *et al*., 1999, with all data available from HR Wallingford) and investigations showing the importance of including complex wave conditions in beach response modelling for areas influenced by significant swell waves (Hawkes *et al*., 1997).

This earlier research tended to treat “shingle” beaches as comprising only gravel with no cross-shore, vertical or temporal variations in sediment size distribution (Coates and Mason, 1997). It was recognised very early in the research that this simplistic approach would need to be extended to beaches of mixed sand and gravel (Powell, 1990). The research reported here begins to tackle the problems of developing predictive methods that consider the more realistic situation of beach sediment distributions that vary over time and location. Beyond this there is work required to further develop methods to model transport processes along the shore and around structures.

An extensive literature review of related research has been written up as part of the HR Wallingford sponsored PhD thesis (Lopez de San Román-Blanco, 2003). This work is presented as an attachment to this report.

3 CHARACTERISTICS OF MIXED BEACHES

The sedimentary composition of mixed beaches is highly variable but some general trends have been outlined from the analysis of 158 sediment curves collated for locations around the English coast. From the study of the different sediment grading compositions available, it is clear that there is not a unique type of beach that could be defined as mixed sediment. However, there are frequently observed patterns that can be considered as typical. Examples of mixed beaches are given in Plate 1.

a) Isle of Sheppey

b) Hastings

c)Twywn, West Wales

d)Mappleton, Yorkshire

Plate 1. Examples of mixed beaches in the UK

Mixed sediment beaches from the samples examined have a bimodal or gap graded composition, with one mode in the sand fraction (sizes ranging 150µm to 500µm, D_{50} around 300µm) and another mode in the gravel fraction (sizes ranging 5mm to 30mm, D_{50} between 10mm and 20mm). The percentage of the sand mode is approximately 20-30%, although this can range up to much higher values (Figure 1 presents a typical sedimentary composition).

There is generally a predominance of gravel at the surface, particularly on higher energy beaches or during stormier seasons, but this often decreases rapidly with depth and can vary markedly over different seasons and sea conditions. It is usually seen that the gravel fraction coarsens both landward and with depth below the beach face. The size distribution of the sand fraction is not so obviously variable with depth or along the profiles, but this may be a reflection of sampling and analysis methods; beach trenches often reveal a layered sediment structure, including bands of sand, shell fragments or gravel, presumed to reflect a time series of varying erosional and depositional conditions. Importantly, it is found that the overall composition of mixed beaches is very variable not only spatially (alongshore, across-shore and in depth within the sediment) but also as temporally (in different time-scales: daily and seasonally).

Two basic foreshore types are recognised:

- lower sand platform and a steep upper gravel ridge, with a very variable area of mixing at the boundary, typical of meso and macro tidal conditions
- fully mixed beaches typical of micro and meso tidal conditions, with a variable cross-shore sediment distribution ranging from a higher percentage of sand across the lower beach to predominantly coarse gravel and cobbles along the storm crest.

Understanding of these beach types can be made more complex by the presence of an impermeable clay or bedrock sub-strata, or structures such as groynes or seawalls.

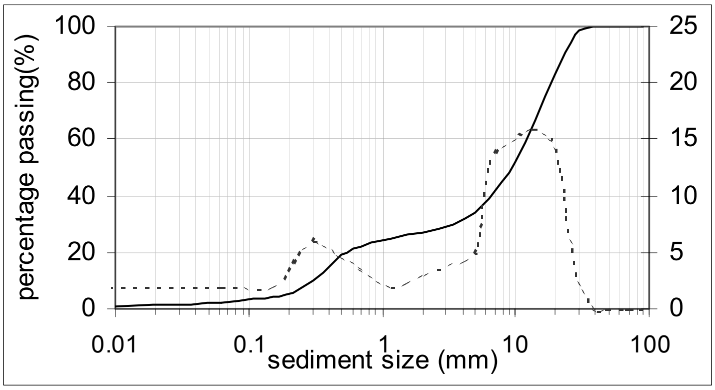

Figure 1. Typical sediment distribution for a UK mixed beach (cumulative and size distributions)

4 PROJECT METHODOLOGY

In order to achieve the project aims outlined in the introduction, a programme combining desk studies, field work, experimental programme and numerical modelling was followed over the 3 year period (Figure 2).

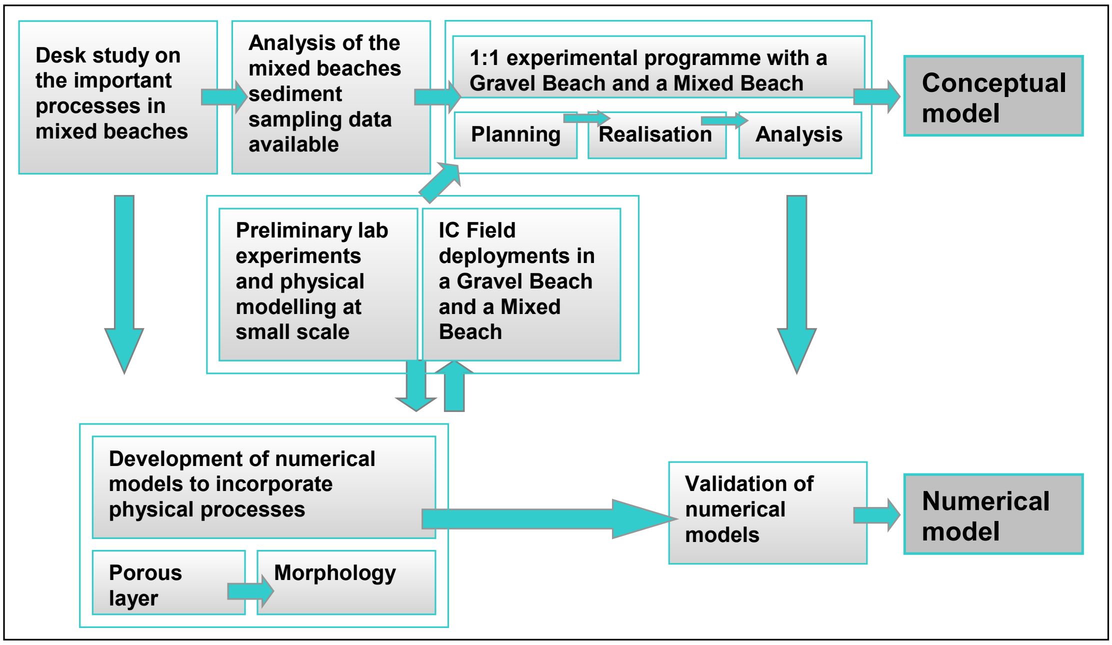

Figure 2. Project methodology (IC is Imperial College)

4.1 Review

A very extensive literature review was undertaken covering all relevant UK and international research. This review has been presented within Lopez de San Roman-Blanco (2003) and is included unedited as an appendix to this report. Some supplementary discussions are set out below.

Existing predictive methods are available to assist shoreline management, including physical and numerical models. Physical models are divided into flume and wave basin models, each providing valuable information. Numerical approaches are broadly divided into parametric models, often derived from observed results in the laboratory or from field measurements, and physics based models which attempt to account explicitly for the main physical processes active across the foreshore.

Each of these approaches has weaknesses and strengths, but none is able to simulate all of the important and complex processes influencing mixed beaches.

4.1.1 Physical models

The use of physical models for shoreline management is normally limited by available facilities and costs. Mobile bed modelling at small scales is further limited by the necessity to work out a compromise between the requirements of the different processes that must be simulated. There are three physical variables that can be used to achieve an acceptable beach simulation:

- grain size and distribution
- sediment density
- time.

Acceptable approaches to scaling narrow graded gravel beaches using low density mobile bed material have been used for over 25 years (Powell, 1990), by compromising between the requirements for simulating:

- fall velocity (on-offshore motion)
- threshold of motion
- permeability (beach steepness).

An additional requirement, not covered by Powell (*op.cit.*), is to distinguish between bedload and suspended sediment load). Despite the use of this approach for the design of numerous beach management schemes, it is clearly recognised that true physical similarity can only be achieved at 1:1 scale.

Sand beach processes are even more difficult to scale as there is a lower limit on the grain size of non-cohesive sediment to use in the model and there is no ready supply of alternative lower density, fine grained material. This only leaves time as a useful scaling variable, and again a 1:1 scale for all variables is required to avoid scale effects. As yet no research has been done to prove the validity of sand beach physical models, and their use for beach management schemes must be seen as providing only qualitative information as part of a wider design process.

Attempting to physically simulate beach processes for any mixture of sand and gravel is even more severely limited as the existing methods used for small scale modelling of sand and gravel are incompatible within the same model. Normal practice is for one fraction of the sediment to be ignored, with the assumption that the other material, usually the gravel, is dominant in relation to the shoreline management requirements.

A more complete discussion of physical modelling limitations and benefits can be found in HRW (1998). It should be noted that physical models have the advantage of allowing realistic short crested and multi-directional wave conditions to be applied through the use of multi-element paddles and defined wave spectra that include appropriate combinations of swell and wind sea conditions.

4.1.2 Numerical models

Existing numerical models are also limited in many ways. Most have been derived for sand beaches and have then been extended to include a wider range of grain sizes. The main problems with respect to extending these models to mixed beaches are set out in Mason and Coates (2001), as follows:

- Assuming a simplistic description of beach sediment, usually by attempting to define the complete beach by a single D_{50} value, although some authors suggest other simple parameters.
- Assuming that sediment distributions do not vary across-shore, along-shore, vertically or over time. Some work has been done to incorporate cross-shore banding as a first step towards including variations. In the UK this has been applied at a relatively simple level to separate longshore transport along lower beach sand platforms from upper beach gravel ridges. This can result in varying drift rates, and sometimes opposing mean long-term directions for different materials.

- Assuming an impermeable surface and ignoring flows within the beach face (infiltration and exfiltration). This is generally acceptable for sand beaches, but not for gravel where higher porosity results in asymmetric flow in the swash zone, giving steeper beach faces and distinct crest formations.
- Assuming a simple threshold of motion based on the defined grain size. On mixed beaches the threshold is influenced by the wide range of grain sizes, by the interactions between grains and by the cross-shore variations in ground water flows.

If these assumptions are held to be inappropriate, the conclusion must be that mixed or gravel beach responses cannot be predicted by simply modifying and re-calibrating existing sand beach models. At present it is generally considered that predictive tools for longshore transport of coarse grained beaches can provide acceptable results when calibrated against appropriate field data, whether based on numerical simulation of appropriate physical processes (e.g. Damgaard *et al.*, 1996) or on equations such as the CERC formula (e.g. Brampton and Motyka, 1984, or Damgaard and Soulsby, 1996). In contrast, cross-shore numerical models have had limited success – mainly due to a lack of knowledge of the governing physical processes and/or an inability to model the processes adequately. Hence no process-based model is available to predict the response of a coarse grained or mixed beach to a given hydrodynamic forcing. HR Wallingford is currently working on the extension of OTTP-1D (one-dimensional swash zone model with a porous layer) towards a morphological capability (Clarke and Damgaard, 2002), but as yet this work is incomplete.

4.1.3 Parametric models

At present parametric models of gravel beach cross-shore response include the work of Powell (1990), known as SHINGLE, and van der Meer (1988), known as BREAKWAT. These models are based on extensive scaled laboratory flume tests - small scale with anthracite by Powell and both large and small scale with gravel by van der Meer. Parametric models for mixed-grained beaches have not been developed, but the present report suggests a number of new parameters that should be included to allow reasonable simulation.

4.2 Experimental procedure

A combination of small scale process experiments and large scale beach simulation experiments were undertaken for the project. Small scale laboratory work was performed at HRW and Imperial College to gain a better understanding of some of the key physical processes and to formulate the direction of the research programme:

- Propagation of water pressure through beach sediments. Comparative permeameter tests were undertaken on sand, gravel and mixtures of sand/gravel. The results showed that the response was quasi-instantaneous in all the beds tested over the 500mm length of the sediment column. They also showed the importance of entrapped air in the pores between sediment particles and the consolidation status of the bed.
- Threshold of motion under waves. These tests showed that the exposed surface composition changed with time.
- Hydraulic roughness of gravel and mixed sand/gravel beds. These tests showed that the variability of measurements of bed roughness over the gravel bed were as large as the changes found for different sediment mixtures. Broadly the roughness conformed to established prediction methods but with a large amount of experimental scatter.

In order to overcome the incompatibilities of having both sediment fractions within the same physical scaled model, an experimental programme at 1:1 scale was undertaken. This experimental exercise was based on, and complemented with, a series of full-scale beach deployments at sand, gravel and mixed sediment beaches at three locations throughout the UK (Holmes *et al.*, 2002). A key factor that was observed in the beach deployments was the role of tidal level on the morphology.

The objective of the 1:1 scale experimental programme was to gain understanding of the overall behaviour of mixed beaches. Comparative results between the gravel and mixed beaches help in understanding their differences and similarities.

The experiments[1] were carried out at the Grossen Wellen Kanal (GWK) through funding provided by the European Community under the Access to Research Infrastructures action of the Human Potential Programme (contract HPRI-CT-1999-00101). The flume is a 342m long, 7m deep and 5m wide research facility in the FZK, Hannover, Germany. The flume has a 1:6 permanent asphalt slope, over which the sediment was placed in an initial 1:8 slope, with a minimum depth of sediment of 2m. The set-up of the beach is shown in Figure 3. The beaches were not reshaped during the experimental procedure, so that the initial condition for each test was the final profile from the test before.

[1] A collaborative effort between HRW, Imperial College, New Forest District Council, University of Plymouth, University of Southampton, with support from University of Caen, France, and University of Firenze, Italy

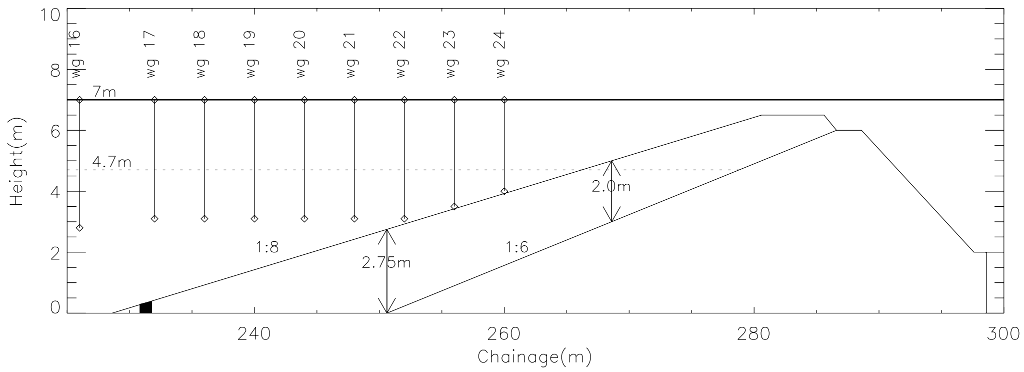

Figure 3. Set-up of experiments (Note distortion of scale; wg is wave gauge)

The programme involved two different beach set-ups:

- Gravel beach consisting of material sieved between 16mm and 32 mm, with a median diameter of $D_{50gravel}$=21mm
- Mixed beach consisting of a bimodal distribution of the gravel used in the gravel beach and sand, which had a D_{50sand}=300µm. The percentage of sand in the mixture was around 30%. The sediment was thoroughly mixed both prior to beach construction outside the flume and during beach construction within the flume.

During initial planning it had been intended that the mixed beach work should be separated into two series, the first with 20% sand content and the second with 40% sand. This additional work would have allowed much greater investigation of the influence of sediment distribution and would have provided much greater confidence in the results with regard to UK beach management. Unfortunately the limitations on facility access and EU funding resulted in the proposed programme being simplified to a single mixed beach series for comparison with the gravel beach series.

a) Installed Gravel Beach

(looking towards wave paddle)

b) Test example

(looking towards the end of the beach)

Plate 2. Experiments at GWK, Hannover

4.2.1 Test programme

The core programme of the experiments, carried out on the different beaches, comprised a total of 5 wave spectra, with significant wave height ranging from 0.6m to 1.1m and wave steepness (H_s/L_m) from 0.01 to 0.03, plus two regular wave conditions. Each test consisted of a series of sequenced batches of waves, all of them with the same wave spectra, but different time series and duration, allowing investigation of beach processes and profile development over time. Several series were run with changing water depths to simulate beach evolution over a tide cycle.

The experiment involved making measurements of surface elevations along the flume, surf and swash velocities, internal pressures, run-up, and sediment distributions at different points along the flume and profile changes. The experimental programme and data are fully described in HRW (2002) and Lopez de San Román-Blanco & Holmes (2002).

The findings from the GWK experiments set out below include:

- Main processes influencing gravel and mixed beaches;

- Validation of two cross-shore empirical models developed previously for gravel beaches, and their applicability to mixed beaches as opposed to gravel beaches (i.e. with no sand in them or small amounts of sand); and,
- Derivation of formulations for the berm crest and the step elevation at the breaker location, plus other morphological and hydrodynamic predictors.

4.2.2 Main processes in mixed beaches

One can characterise beaches in terms of their permeability with gravel beaches at one end of the spectrum and fine sand beaches at the other end. In between both, the broad category of mixed beaches would be situated (Figure 4). This is a simple classification believed to be adequate and useful for the description of the different behaviours encountered and the physical processes associated with different beaches. However, one has to keep in mind that permeability is not a "bulk" parameter for the whole beach and cannot be obtained from a single sample of beach sediment. This is especially important in the case of the mixed beaches where the measured permeability can vary by orders of magnitude depending on the cross-shore location of the sample and its depth within the beach.

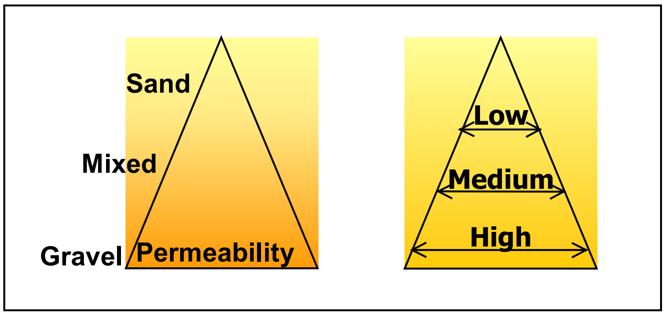

Figure 4. Classification of beaches – variation of permeability with sediment composition

In the case of the gravel beaches, the rapid percolation of the water through the beach-face is a key physical process. Its main implication is the weakening of the backwash flow and therefore there is a resulting reinforcement of onshore transport. This does not imply that erosion cannot take place under certain conditions.

For mixed beaches, the swash/backwash process operates somewhat differently and there is a major influence from the elevated water table within the beach. Although the sediment is quite permeable, especially when comparing to a beach comprising just of sand, the fact that the beach-face is water-logged for most of the time due to an elevated water table impedes the infiltration of the water through the sediment. This promotes exfiltration through the beach-face between still water level (SWL) and the level of the elevated water table in the beach, with the local effect of increasing the backwash.

From comparison to published information for sand beaches, it appears the backwash in the mixed beach case is still not as large as that found on a sand beach. However, the associated sediment transport is of a smaller magnitude than that found on the gravel beach and hence the difference between onshore and offshore transport is less pronounced.

A direct consequence of the saturation within the beach is the fact that the incoming bore runs-up the beach, maintaining it wet, with a lens of water over it. This has an influence in the position of the static and dynamic shoreline[2], which in the mixed beaches are always "landwards" of their position for the gravel beaches under the same wave and water level conditions. Consequently, the associated value of the set-up at the shoreline is also larger for the mixed beaches.

Regarding internal processes in the beach, vertical hydraulic gradients occur when the pressure head measured at two different positions (in the same horizontal, but different elevation) differs from the hydrostatic pressure. Normally, upwards hydraulic gradients will occur where there is a local minimum pressure head (i.e. under the backwash), whereas downwards hydraulic gradients will occur during a local maximum head (i.e. under the swash uprush). These vertical gradients have been found to increase when the intensity of the incoming waves, as measured by the deep water wave parameter H_0L_0, increases. For the gravel beaches, the vertical hydraulic gradients are very small. However, for the mixed beaches, these vertical hydraulic gradients are larger, leading to the possibility of vertical flows within the beach. Downwards gradients are usually larger than upwards ones.

Slope-parallel hydraulic gradients have also been defined in order to get a feeling for the flows in the cross-shore direction. In the case of the mixed beaches, down the slope hydraulic gradients prevail because of the higher internal head leading to the exfiltration referred to above.

The response of the groundwater to the incoming waves in both beaches has been found to be noticeably different. In gravel beaches the speed of the groundwater response is quicker with a maximum value of the order of 1m/s compared with the mixed beaches which

[2] The dynamic shoreline is the intersection of the set-up with the beach profile.

was of the order of 0.8m/s. In both cases the speed diminishes with the square root of H_0L_0. Also, because of the lower drainage capacity of the mixed beaches in comparison to the gravel beaches, the groundwater response is cumulative in time, as if the water table had a "memory" for the previous wave conditions.

All these findings have been collated in a conceptual model (Figure 5) based on the classification of the beaches in terms of their permeability, as explained in Figure 4. In Figure 5 the arrows linking symbols represent cause-effect relationships. The symbols are used to convey how each component varies with beach composition (permeability), i.e. high, medium or low. In each case the top of the symbol denotes sand and the bottom gravel as shown on the left hand side of the figure. For example the component "backwash" indicates high backwash for sand beaches and low backwash for gravel beaches.

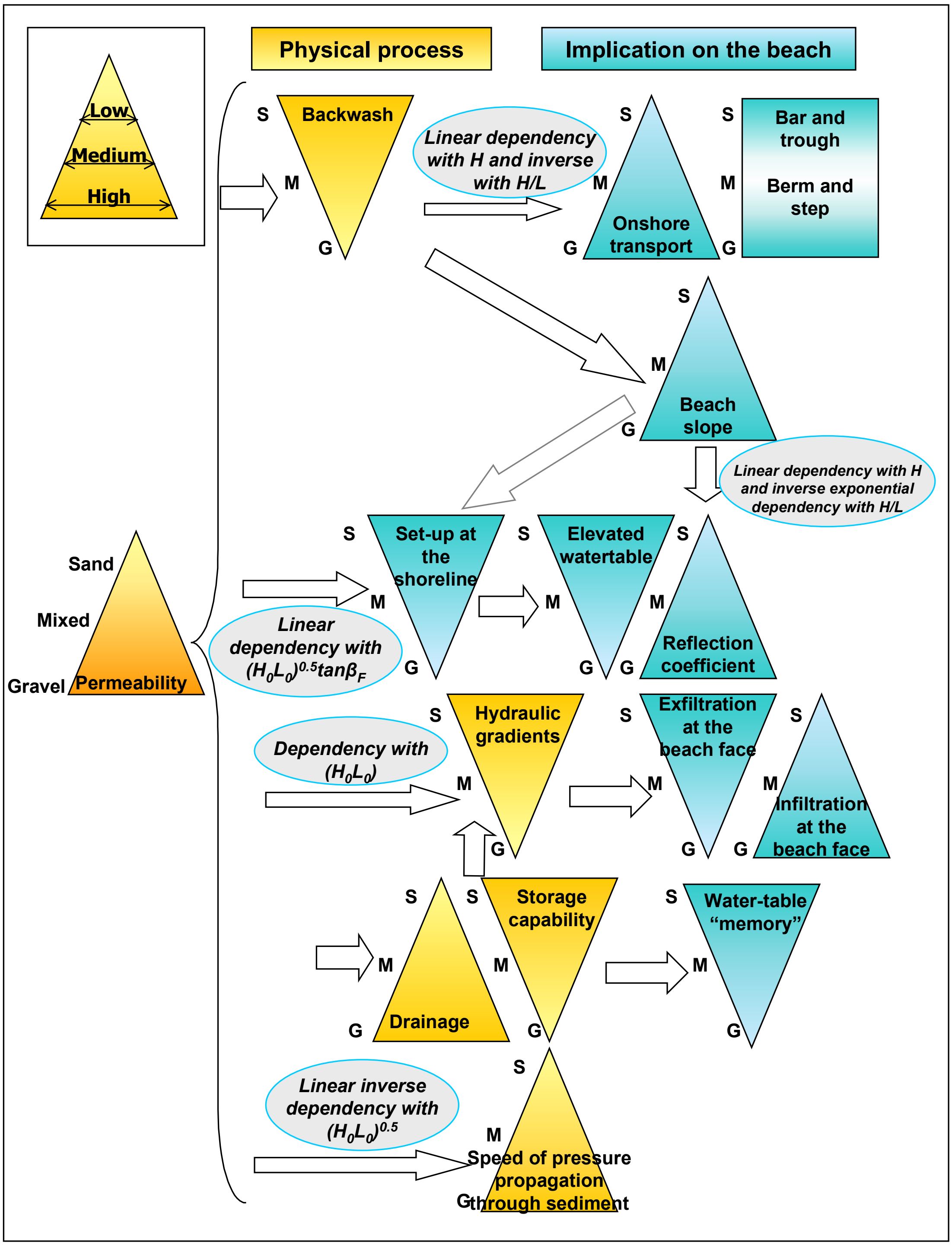

Figure 5. Conceptual model for beach processes; the width of the triangle indicates the relative magnitude or importance of the behaviour for Gravel – Mixed – Sand beaches (from Blanco *et al.*, 2003)

4.3 Validation of cross-shore empirical models

4.3.1 Predictive parametric models

A comparison with the available predictive methods for gravel beaches, SHINGLE (Powell, 1990) and BREAKWAT (van der Meer, 1988) was carried out (Lopez de San Román-Blanco & Holmes, 2002). Both are parametric models derived from an extensive programme of scale laboratory experiments developed for the prediction of beach profiles after a storm.

Overall, SHINGLE and BREAKWAT give a reasonable estimation of the profile response to the wave conditions when comparing them to the measured profiles from the GWK experiments for the gravel beach. For example, the test result in Figure 6 shows the corelation between SHINGLE and the GWK results part way through a test, with a good prediction of berm crest chainage (around 267m) but an underprediction in berm height by about 0.3m, which would increase further as the beach reached equilibrium with the test conditions. From an engineering point of view this underprediction introduces an element of doubt if the results are to be used for determining an appropriate recharge volume or an elevation for beach reprofiling. SHINGLE will indicate a significantly lower required beach volume than the GWK results would suggest, and these volumes would be even greater if the effects of combined swell and wind sea were also included as suggested by Hawkes *et al.,* (1997).

Another parameter considered is the chainage of the start of the active beach (i.e. how far up the beach is the morphology modified for a given wave input). BREAKWAT predicts the position of the start of the beach with accuracy; although for longer wave periods it underestimates it, whereas the SHINGLE prediction is reasonable but always underestimated (by around a metre distance).

This intercomparison gives some confidence in the suitability of using appropriately scaled laboratory models to reproduce realistic profile responses in gravel beaches, although site specific tests should include for complex wave conditions if the area is affected by significant swell (i.e. all south-west and western coasts under the influence of Atlantic conditions).

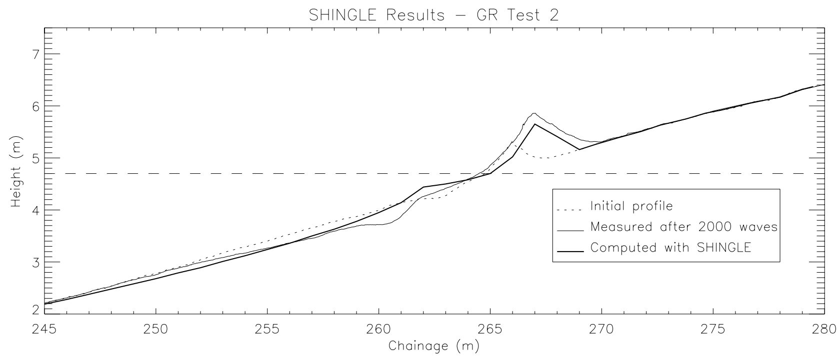

Figure 6. Calculated and measured profile for Test 2 – Gravel beach

Although the sediment characteristics of the mixed beach tests lie outside the range of applicability of the two empirical models, the measured profiles from the GWK experiments were also compared to the predicted profiles from SHINGLE and BREAKWAT. This was considered a necessary exercise in order to evaluate their capabilities.

The main conclusions from this exercise are:

- As the chainage for the start of the active beach is quite similar for the gravel and mixed beaches under the conditions tested, the predictions given by the parametric models are reasonable. This parameter is important from a beach management perspective as it gives an idea of how much the beach will retreat or build up under given conditions.
- As the measured chainage and elevation of the beach step (breaker step below water line) of the mixed beach are quite similar to those measured in the gravel beach, their prediction with the parametric models is also considered reasonable.
- From comparison with all the test data the berm crest chainage (i.e. 267m in Figure 6) is on average underpredicted with the parametric models by around 30%, whereas the crest elevation is overpredicted on average by around 0.5 m. These predictions are not reasonable as the upper beach slope for a mixed beach is likely to be much shallower than the equivalent slope for a gravel beach, and the crest elevation may be considerably lower.

4.3.2 Other empirical formulations

The results from the GWK experiments were used to assess the applicability of other beach process predictive equations. New formulations have been proposed, based on past research for bimodal sediments, beach morphological features and hydrodynamic (wave) parameters (Lopez de San Román-Blanco *et al.*, 2003). Definition of notation is included within the appendix along with discussions of the referenced research. A brief comparison with previous research is given in *italics* below to emphasise the interrelationship with this new work:

- New formula for the crest elevation, so that $B_h = CH_b^{5/8}(gT^2)^{3/8}$ with the coefficient C with the following values:
  - C=0.342 for mixed beaches.
  - C=0.460 for gravel beaches.

  Range of applicability: $H_b^{5/8}(gT^2)^{3/8} = 1.6$ to 4.5.

  This compliments the coefficient of C=0.125 given by Takeda and Sunamura (1982) for sand beaches (Figure 7).

- New formula for the step elevation, so that $z_{step} = C\sqrt{H_b T W_s}$ with the coefficient C taking the following values:
  - C=43 for mixed beaches.
  - C=37 for gravel beaches.

  Range of applicability: $\sqrt{H_b T W_s} = 0.010$ to 0.023.

  This compliments the coefficient of C=0.55 given by Short (1999) for sand beaches and shows a very different magnitude of step elevation formation (Figure 7).

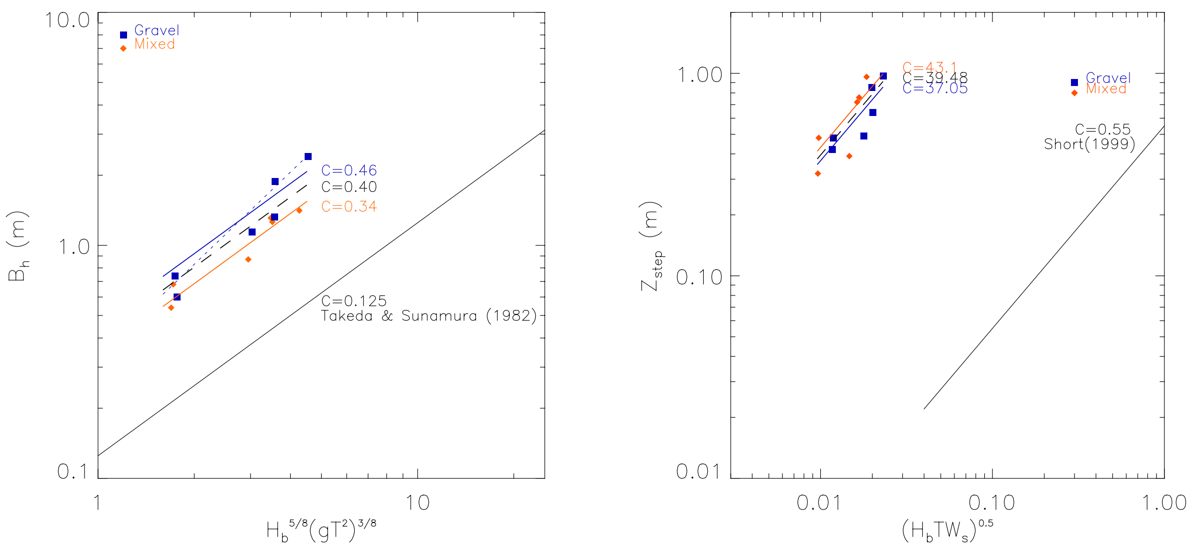

Figure 7. Proposed formulations for the berm height and step elevations (from Lopez de San Román-Blanco *et al.*, 2003).

- New formulas for the dependency of the coefficient of reflection on wave and sediment characteristics:

  Dependency of the coefficient of reflection with Iribarren number: $K_R = \dfrac{C\xi^2}{\xi^2 + 5.5}$ with the coefficient C=0.44 for coarse-grained beaches.

  Range of applicability: $1.2 \le \xi_0 \le 3.2$.

  Dependency of the coefficient of reflection on wave steepness: $K_R = a(H_0 / L_0)^b$ with the coefficients a and b:

  a=0.0045 b=-0.96 for gravel beaches.

  a=0.052 and b=-0.23 for mixed beaches.

  Range of applicability: $0.009 \le H_0/L_0 \le 0.03$.

  And a=0.0263 b=-0.43 for coarse-grained beaches in general *(using data from Powell, 1990).*
  Range of applicability: $0.005 \le H_0/L_0 \le 0.06$.

- New formulas for the dependency of the set-up at the shoreline on wave and sediment characteristics of the type: $B_s = C(H_0 L_0)^{0.5} \tan\beta_F$ where the coefficient
  - C=0.15 for mixed beaches.
  - C=0.05 for gravel beaches.

Range of applicability: $1<(H_0L_0)^{0.5}\tan\beta_F<6$.
This compliments the coefficient C=0.45 given by Hanslow and Nielsen (1993) for sand beaches.

- New formulas for the dependency of the asymptotic over-height on wave and sediment characteristics of the type: $B_\infty=C(H_0L_0)^{0.5}\tan\beta_F$ where the coefficient
  - C=0.115 for mixed beaches.
  - C=0.056 for gravel beaches.

  Range of applicability: $1<(H_0L_0)^{0.5}\tan\beta_F<6$.
  This compliments the coefficient C=0.55 given by Nielsen and Kang (1995) for sand beaches.

- A relationship for the mean speed of propagation through the sediment in relation to the parameter $(H_0L_0)^{1/2}$ has been derived. This relationship is of the type $C_{sediment}=A-0.08(H_0L_0)^{1/2}$ where A is a coefficient dependent on the sediment properties, i.e. permeability. The values proposed for A are: A=1.09 for gravel and A=0.79 for mixed.

5 ONGOING DEVELOPMENT OF NUMERICAL CROSS-SHORE MODELS WITH “PERMEABILITY”

The existing HR Wallingford swash zone cross-shore numerical model OTT1D was extended to include a porous layer as described in Clarke *et al*. (2002). The new OTTP-1D model is capable of predicting wave processes on the beach, water velocities in the swash zone on the beach, overtopping of the beach crest and the flow over the impermeable core. An example of the model output is included in Figure 8. This shows how the water table in the beach develops during a swash event overtopping the impermeable core and leading to a discharge which can then flow out of the backface of the beach.

The further development of OTTP1D into a mixed beaches cross-shore morphological model was planned as part of this project. So far the cross-shore morphological modelling capability for gravel beaches has been developed and implemented. Early validation results are encouraging. However, due to the complexity of the behaviour of mixed beaches as detailed earlier in this paper, the development of a mixed beaches cross-shore modelling capability within OTTP will require further research effort beyond the scope of the present project.

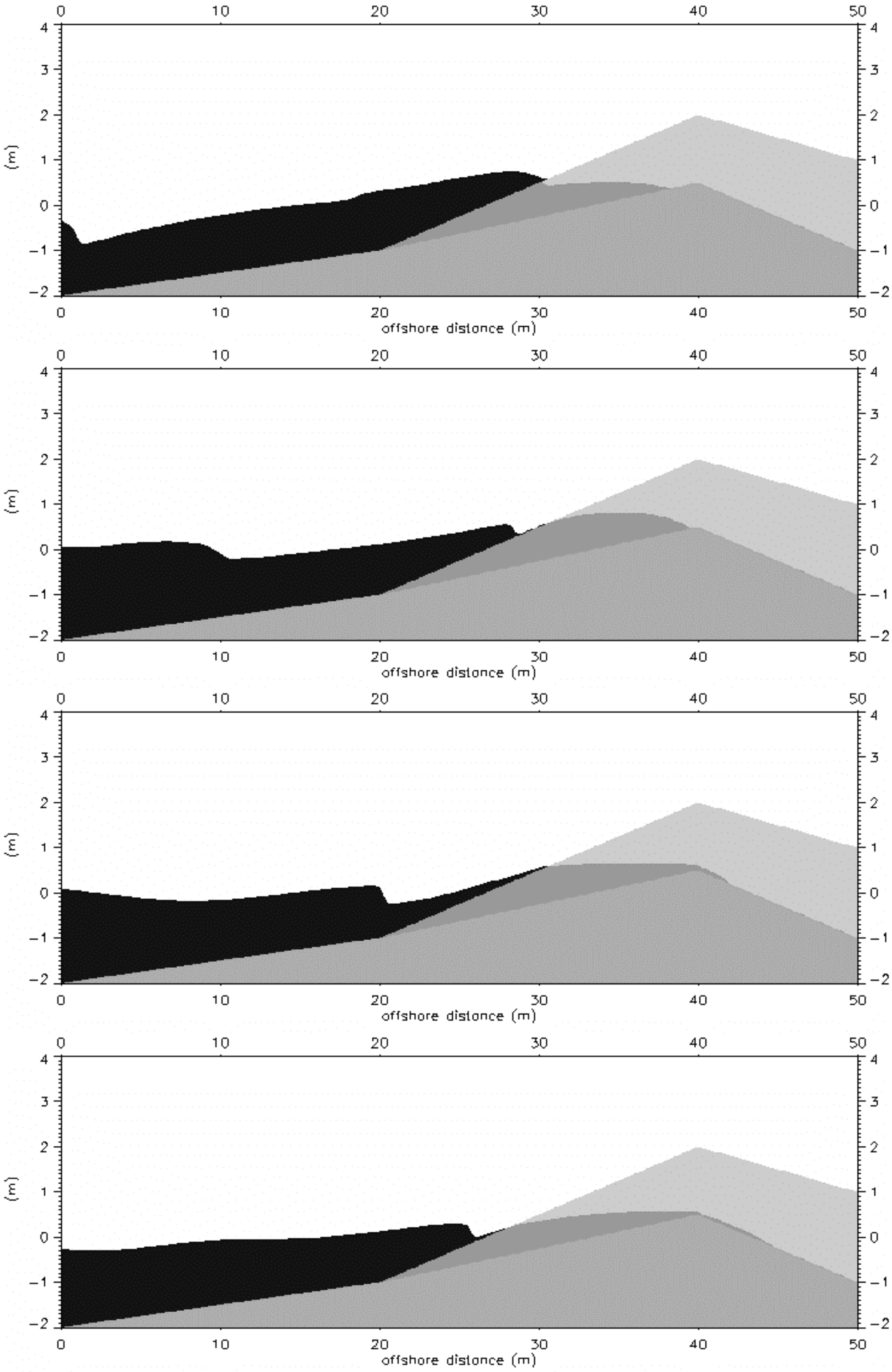

Figure 8. Water table response to incident surface waves for a gravel beach with an impermeable core

6 CONCLUSIONS AND RECOMMENDATIONS

The aims of the mixed beach project were successfully concluded and have been communicated through papers and reports as well as conference and workshop presentations. The research has yielded a significant step forward in understanding the key cross-shore processes involved and this has identified further research to improve UK beach management methods. Full details of the research are published in HRW (2002), Lopez de San Román-Blanco (2003) and Lopez de San Román-Blanco *et al.* (2003). The following section summarises the conclusions and recommendations.

- There is not a unique type of beach that can be called a mixed beach. However, there is a pattern frequently observed that could be seen as a "typical" mixed beach in the UK. These types of beach have a bimodal composition, with one mode in the sand fraction and another in the gravel fraction, so that the percentage of the sand is approximately 20-30%. The composition of these beaches is very variable spatially (alongshore, across-shore and in depth within the sediment) as well as temporally (in different time-scales: daily and seasonally).

- The performance of currently available empirical predictive tools has been examined. Good performance of the parametric models BREAKWAT and SHINGLE were found when applied to gravel beaches. This was as expected because the methods were originally devised for gravel beaches (from scaled tests in the laboratory). When applied to mixed sediment beaches, they produced broadly the right results but should only be used as qualitative tools together with the conceptual model of beach processes presented in this paper and new formulations proposed for crest and step elevation based on extensions of existing formulae for sand beaches.

- The application and role of existing HRW numerical cross-shore model with permeability and morphological predictive capability (OTTP 1D) have been explored. The model is suitable for predicting wave processes, velocities, overtopping of the beach crest and flow over an impermeable beach core. Early validation results for the morphological model of gravel beaches are encouraging. However, due to the complexity of the behaviour of mixed beaches as detailed earlier in this paper, the development of a mixed beaches cross-shore modelling capability will require further research effort beyond the present project.

- From the analysis of the experimental data, the understanding of the processes that prevail in coarse-grained beaches and their inter-relationship has been broadened. This has been collated as the conceptual model presented in Figure 5 and summarised below.

    1. Permeability is the key physical parameter that distinguishes beach form and response. However, it is difficult to determine in the case of mixed beaches as they can vary by orders of magnitude depending on the cross-shore location of the sample, its depth within the beach and the recent evolution of the beach response to waves and tides.

    2. The rate of percolation through the beach-face influences the strength of the backwash flow and therefore the balance between offshore and onshore transport.

    3. There is a major influence from the elevated water table within the beach. If the water table is high, the beach-face is water-logged for most of the time and this impedes the infiltration of the water through the sediment. From comparison to published information for sand beaches, the backwash in the mixed beach case is not as large as that found on a sand beach.

    4. The positions of the static and dynamic shorelines for mixed beaches are "landwards" in comparison to their positions for gravel beaches under the same wave and water level conditions. Consequently, the associated value of the set-up at the shoreline is also larger for the mixed beaches.

    5. Vertical hydraulic gradients within mixed beaches are larger than those in gravel. Slope-parallel hydraulic gradients have also been defined in order to get a feeling for the flows in the cross-shore direction. In the case of the mixed beaches, down-slope hydraulic gradients prevail because of the higher internal head leading to the exfiltration from the beach face between the water line and the run-up limit.

Recommendations for future work
Although the present research represents a significant step forward in understanding the key cross-shore processes involved, it has also identified further gaps in knowledge:

- From the beginning of the project the potential importance of the different modes of transport of the sand and the gravel, and their interaction when mixed was recognised. However, more research in this area is needed. The 1:1 scale experiments showed that gravel moved inshore to form a berm crest, whereas the movement pattern of the sand was less clear. Some sand apparently infiltrated down into the sediment forming a distinct layer of gravel overlying mixed sand/gravel. With the data available it could not be concluded that sand had "winnowed" out of the bed and had moved offshore because no sand deposits were found at the base of the beach.

- The conclusions on the behaviour of a mixed beach compared to a gravel beach are based on the testing of two beaches only, due to the limited access to the GWK facility and the length of time required to complete each test series. Based on the results obtained, it is expected that mixed beaches with a high percentage of sand (gravel particles within a full matrix of sand) would behave more like a sandy beach. Similarly, mixed beaches with a low percentage of infilled sand would behave more like a gravel beach. Therefore, investigations of a wider range of sediment mixtures through experimental and field work are required to determine the influence of initial sediment mix on beach evolution before our understanding of processes is sufficient to develop widely applicable predictive tools.

- Laboratory experiments on the inter-dependency of sediment characteristics and distribution should be carried out. The results from this experiment will give formulas for porosity, permeability, pore diameter distribution (and therefore associated capillary effects) in terms of the fraction sizes and percentages.

- The influence of the tide should be further examined, as it has been seen to be of great importance, especially to processes within the beach.

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9 Appended File

Literature review from the PhD Thesis *Dynamics of gravel and mixed, sand and gravel, beaches* presented by Lopez de San Román-Blanco, 2003 (Chapters 2 and 3).