

Sediment Transport Processes on Mixed Beaches: A Review for Shoreline Management

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ABSTRACT

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Mixed beaches are a comparatively neglected area of coastal research, other than for sedimentological investigations or relatively long-term geomorphological change. The paper reviews the progress of research into processes of sediment transport on mixed sand and gravel beaches since 1980, including fieldwork, laboratory studies and modelling. First-order and secondary factors are identified. The hydraulic conductivity of the bulk sediment is found to be an influence on swash and backwash infiltration and groundwater flow through the sediment. No existing transport model contains the most significant factors for mixed sediment transport, which should include swash and backwash hydrodynamics, infiltration, steep beach gradients, fractionation and differential hydraulic conductivity. Near-prototype scale physical model tests of profile response are needed, since mixed sediments cannot be scaled correctly for both hydrodynamic response and hydraulic conductivity.

ADDITIONAL INDEX WORDS: *Gravel, shingle, field measurements, laboratory measurements, hydraulic conductivity, permeability.*

INTRODUCTION

The vast majority of research into coastal hydrodynamics and associated sediment transport has been concerned with beaches comprising a single sediment type (sand or gravel); in contrast, beaches containing a mixture of both sand and gravel have aroused only sporadic interest. Although comparatively rare on a world-wide scale, mixed sediment beaches occur commonly around the shores of regions where the effects of glaciation have provided an abundant source of sands and gravels for subsequent re-working by Holocene rising sea levels, including the UK¹, Eire, Canada and the Arctic Sea coast (e.g. CARTER *et al.*, 1990a; FINKELSTEIN, 1982; HILL, 1990), Tierra del Fuego (BUJALESKY and GONZÁLEZ-BONORINO, 1991) and New Zealand (e.g. KIRK, 1969). They are recognised as being morphologically distinct from and more complex than either sand or gravel beaches (KIRK, 1980), but very little is known about the basic factors that distinguish the processes of sediment transport on mixed beaches from the processes on single sediment beaches.

Although MCLEAN (1970) considered mixed beaches as having roughly equal proportions of end-member populations (sand and gravel), there is no clear definition of what proportion of sand or gravel is required before a beach can be considered "mixed". The term "mixed" is also used to describe beaches which consist of a mainly gravel bank or ridge, with

a gently-shelving, sandy terrace exposed at low water (Figure 1). In reality, even beaches which appear superficially to be composed of gravel rarely comprise only coarse material, but often contain temporally-varying proportions of sand and gravel both across- and alongshore (Figure 2). Sand content usually increases vertically downwards to a relatively impermeable core. Most mixed beaches have a composite profile, with a noticeable break of slope between the gravel section and the lower foreshore so that, almost invariably, the low-tide beach is of a dissipative nature, with an abrupt switch to reflective conditions at mid- or high tide (WRIGHT and SHORT, 1984). The CIRIA Beach Management Manual (SIMM *et al.*, 1996, p 49) describes typical characteristics of various beach types, including beach slope, D_{50} , grain size curves, grading and tidal coverage, though without a working classification. Examples of reported sediment proportions include: an average 30% sand in Suffolk, (PONTEE, 1996); less than 20% sand at Carnsore, south-eastern Ireland (ORFORD and CARTER, 1985); 30% gravel and 53% sand on a mixed barrier on the Canadian Beaufort Sea coast (HILL, 1990); between about 15 to 50% sand along a lengthy section of beaches and barriers in Washington State, USA (McKAY & TERICH, 1992); 68% sand at Kaikoura but 48% sand further along the coast at Canterbury, New Zealand (KIRK, 1980); between 17% and 63% sand at various sites along Palliser Bay, North Island, New Zealand (MATTHEWS, 1983).

In recent years, the importance of understanding mixed beach processes has come to prominence due to increasing use of coastal engineering schemes involving beach replen-

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¹ In the UK, gravel beaches are often referred to as shingle beaches.



Figure 1. Morfa Dyffryn, North Wales, UK.

ishment. Indeed, in the US, beach nourishment is now the preferred option for short-term stabilization of any eroding coastline which is used for recreation or tourism. Along the south and east coasts of the UK in particular, such schemes are generally designed for gravel-sized sediments, given that gravel beaches are known to be an efficient form of sea defence (POWELL, 1990). However, in a number of schemes *e.g.* Seaford, Eastbourne, Hurst Castle Spit, the borrow material is dredged from offshore and inevitably contains a significant proportion of sands and fines. Consequently, mixed beaches are now of considerable topical interest both in sediment transport research and coastal engineering terms, but there is limited understanding of their behaviour. Typical examples of the problems faced by shoreline managers are:

- inability to determine the sensitivity of the beach profile and cross-sectional area to variations in sediment distributions
- uncertainty in predicting longshore or offshore losses of recharge material over time
- inability to predict beach response in the vicinity of coastal structures
- inability to predict the importance of seepage through barrier beaches.

Undoubtedly, the large-scale morphological behaviour and evolution of any beach system over time scales of decades to centuries is determined primarily by the twin factors of sediment supply (both antecedent and continuing) and relative sea level rise (FORBES *et al.*, 1995), superimposed upon any

change in climatic forcing. For example, multiple barrier ridges have been reported where supply of sediment is high, in contrast to a single, asymmetrical ridge where the supply of sediment is lower (CARTER and ORFORD, 1984). MCKAY and TERICH (1992) also illustrated the role of sediment supply along a lengthy section of complex beach/barriers in Washington State, USA, which had evolved during the Holocene and which is subjected to similar, high-energy conditions. Where the sediment supply has been reduced, the beach crest was lower and overwashing and overtopping were more frequent. In contrast, where sediment input from riverine deposits and eroding cliffs was high, the height of the beach crest was maintained and fewer instances of overwashing occurred. FORBES *et al.* (1995) illustrated the self-organisation of gravel and mixed barrier systems through long phases of gradual evolution interspersed with short periods of rapid restructuring and, in a later paper, concluded that antecedent conditions (beach slope, barrier crest height etc.) were a major determinant of coastal recession rates over decadal time scales (FORBES *et al.*, 1997).

These geomorphological/sedimentological aspects of mixed beaches are what have been most widely investigated over the past 20 years. However, although any underlying geomorphological trends should not be neglected, the questions raised by management of present-day mixed beaches cannot be answered by sedimentological investigations alone, but must encompass detailed process studies of the type conducted widely on sand beaches and, more sporadically, on



Figure 2. Hayling Island, Hampshire, UK.

gravel beaches. Accordingly, the emphasis in this paper is upon the relatively short-term processes which determine the response of a mixed beach on the scale of tides to years. In particular, from a management point of view, it is useful to identify when it is no longer acceptable to regard the process response of mixed beaches as analogous to either those of pure sand or pure gravel.

The aims of the review are fourfold: (i) to consider the processes which most influence sediment transport on mixed beaches; (ii) to examine the suitability of existing sand and gravel sediment transport models for mixed beaches; (iii) to assess the contribution of field and laboratory studies since the last review of processes on mixed beaches by Kirk in 1980; and (iv) to highlight areas where future research should be concentrated.

FACTORS INFLUENCING SEDIMENT TRANSPORT ON MIXED BEACHES

Sediment transport prediction depends on an understanding of many inter-related factors. This review concentrates on investigating those factors that may have a particular influence on mixed beach transport, including an assessment of what are considered to be first and second order factors. The existing research is outlined; it is shown to be limited and, in some cases, contradictory.

First Order Factors

Hydraulic Conductivity

Perhaps the most distinctive property which distinguishes a mixed beach is the hydraulic conductivity which, in turn, has an important influence on sediment transport processes and swash zone hydrodynamics. There are two inter-related routes by which the hydraulic conductivity of the sediment exerts a control over transport on mixed beaches: the beach profile and groundwater flow. Hydraulic conductivity was first suggested as a primary control on beach slope by INMAN and BAGNOLD (1963) and SHEPARD (1963) and later verified by the laboratory experiments of QUICK (1991), QUICK and DYKSTERHUIS (1994) and HOLMES *et al.* (1996). Further details of the laboratory experiments are given below. QUICK and DYKSTERHUIS (1994) suggested that waves breaking on a permeable beach produce a net onshore shear stress over the swash and backwash cycle, leading to net onshore transport and profile steepening, until equilibrium is reached; thus the hydraulic conductivity of the beach is directly responsible for the steeper profile. Alternatively, the field and laboratory investigations of CARTER *et al.* (1990b) and POWELL (1988) respectively, attribute the steeper profile to greater energy dissipation through increased bed roughness of a mixed/gravel beach.

Permeameter tests show that the hydraulic conductivity of sand/gravel mixtures is markedly reduced once the sand con-

tent exceeds about 25% (MASON *et al.*, 1997). This effect is particularly noticeable when the sand admixture is fine sand; an increase in sand content from 20 to 30% is accompanied by a reduction in hydraulic conductivity of two orders of magnitude. This finding is in contrast to HAZEN (1911, quoted in QUICK and DYKSTERHUIS, 1994), who considered that the finest 10% fraction determined hydraulic conductivity, but is probably due to the increasing void ratio/decreasing porosity of what are effectively bi-modal sediments. In general, the percentage of sand required to produce a given reduction in hydraulic conductivity will vary with both the size and grading of the gravel material, since both properties determine the void ratio of the bulk sediment. Nevertheless a sand content of around 25% appears to be a key value (reducing the hydraulic conductivity of a mixed sediment to approximately that of the sand) since the hydraulic conductivity determines the profile response of the beach. These conclusions suggest that once a mixed beach contains greater than about 25% sand by weight (or 20% for fine sand) in the sediments within a metre or so from the surface, its profile response is not the same as a gravel beach. Increasing amounts of sand (even up to 60%) do not cause sufficiently further decrease in hydraulic conductivity to have much additional effect on the profile response and therefore seasonal variations in sand content of a mixed beach (examples of which are given in the introduction) are unlikely to significantly affect its morphodynamic response.

It should be noted also that hydraulic conductivity is a notoriously variable parameter, particularly in the field (*e.g.* LANDON, 1991) but even for laboratory estimates (BAIRD *et al.*, 1997). Few field measurements of hydraulic conductivity of mixed beaches have been reported. KIRK (1991) refers to two: an unpublished MA thesis by KELK (1974) which considered that a mixed sediment barrier at a river mouth was effectively impermeable (no details were given) and a publication by PEMBERTON (1980) which suggested that a similar barrier had a very high permeability. Model results of groundwater flow across the mixed sand/gravel section of a composite beach in North Wales suggested a hydraulic conductivity representative of the medium sand (MASON, 1997).

On a larger scale, the hydraulic conductivity of the sediment is an important determinant for land drainage flow across mixed sediment barriers (CARTER *et al.*, 1984). Coarse barriers can tolerate significantly higher discharge volumes before the formation of surface channels, so that as the hydraulic conductivity of a barrier decreases, the likelihood of formation of surface drainage across the barrier increases; a small longshore decrease in grain size over approximately 4 km was held to reduce the seepage potential of a mixed barrier in south-eastern Ireland by 35% (CARTER *et al.*, 1984). Erosion caused by seepage was also observed on the back crest of Hurst Castle Spit, a sand/gravel barrier beach, under extreme conditions (NICHOLLS, 1985).

Infiltration and Groundwater

Higher infiltration should occur during both swash and backwash on beaches with high hydraulic conductivity, which should lead to an attenuated run-up spectrum (although little

field evidence exists to support this), whilst POWELL'S (1990) laboratory tests found no dependency between wave run-up and beach material characteristics, although he identified a reduction in crest level (and hence run-up) with a narrowly graded material.

The importance of beach groundwater for sediment transport is increasingly recognised (for a detailed review of groundwater behaviour on sand beaches see BAIRD and HORN, 1996) although, with two exceptions (NICHOLLS, 1985; MASON, 1997), field and laboratory research has been undertaken on sandy beaches. The importance of GRANT'S (1946, 1948) infiltration theory is being re-assessed for sandy beaches (BAIRD *et al.*, 1997). However, the existence, importance and effect of a seepage face on swash zone sediment transport are uncertain for beach sediments with high hydraulic conductivity. On the one hand, the higher infiltration capacity of gravel means that a seepage face, if present at all, is likely to be spatially and temporally restricted; consequently, a certain volume of swash and backwash can be lost through infiltration if the sediment drains in between swashes. On the other hand, backwash is likely to be enhanced by larger volumes of exfiltrating water, at high seepage velocities, resulting from steeper beach gradients and, possibly, non-Darcian flow. In addition, if a mixed sand/gravel layer exists at a depth below the surface that is higher than the tide- and wave-induced fluctuations of the water table, then less energy can be dissipated through percolation than would be expected for a surficial gravel beach (particularly during the ebbing tide).

There are no laboratory or field experiments which have measured differential infiltration during swash and backwash and, at present, no techniques have been developed sufficiently to measure this. The principal drawbacks to quantifying the effects of sediment mixture on swash/backwash and wave run-up are:

- the spatial and temporal variations in sediment mixture
- the mobility of the sediment and often complex beach profile, both of which generally preclude the use of run-up wires
- reversing flows in shallow water, high levels of turbulence and an inhospitable environment, which make the field deployment of electronic instruments extremely difficult and expensive.

The only high frequency field measurements of water table fluctuations from a mixed beach were at Morfa Dyffryn, North Wales, where the groundwater response of the mixed sand/gravel section of beach was found to be not significantly different to that of a sand beach (MASON, 1997). This leads to the conclusion that if a mixed sand/gravel layer exists below the surface at an elevation greater than the tidally-induced fluctuations of the water table, any overlying gravel cannot dissipate much energy through percolation (although energy will still be lost through friction at the sediment/water interface). This is because the sand fraction largely determines both the hydraulic conductivity and specific retention of the mixed sediment, so that sand/gravel mixtures remain saturated for longer than gravel.

Wave Reflection

A second route via which the sediment properties influence the hydrodynamics is through increased wave reflection (since the presence of gravel sediment permits a steeper beach gradient than occurs on an unrestrained sand beach) combined with the loss of energy through infiltration. The importance of the high infiltration capacity of gravel was illustrated by KOBAYASHI *et al.*'s (1991) laboratory experiments, using irregular incident wave trains representing plunging, collapsing and surging breaker types. They found that the presence of a thick, permeable gravel layer on a 1:3 sloping beach reduced wave reflection, with corresponding reduction in wave height in comparison with the reflection from the impermeable slope. In fact, it proved impossible to generate exactly the same wave train as for an impermeable beach due to this effect. Similar effects were noted in a numerical simulation of the same conditions (KOBAYASHI and WURJANTO, 1992).

POWELL (1988) reported about 10% reflection for all breaking waves. For less steep waves ($H_s/L_m < 0.02$), reflection increased almost exponentially to a maximum of nearly 60%, *i.e.* energy from long, low waves is not dissipated as effectively as for short, steep waves. Neither increasing the D_{50} (from 10mm to 24mm) nor near-doubling of the effective depth of the beach had any notable effect on the reflection coefficient. From this, Powell concluded that the main process of dissipating energy on gravel beaches is through wave breaking and frictional losses at the water-sediment interface, rather than by infiltration processes.

However, neither of these laboratory experiments have concerned mixed sediments and few reports of wave reflection from mixed beaches have been reported. DAVIDSON *et al.* (1994) reported that reflection from a macro-tidal mixed beach at Felpham, West Sussex, varied with tidal stage, with higher reflection coefficients from the steeper upper beach gradient. MASON (1997) also observed a fairly systematic increase in reflection coefficients with rising tidal levels, again linked to a steeper beach gradient. However, the increase in wave reflection was only for the swell wave component ($0.05 < f < 0.1$ Hz); reflection of the wind waves remained quasi-constant throughout the tide, independently of the change in beach gradient. The highest reflection coefficients were in excess of those observed from a porous offshore breakwater, from which BIRD *et al.* (1996) had concluded that 0.6 was the maximum possible reflection coefficient, since remaining energy was dissipated or transmitted through the structure. MASON *et al.* (1997) concluded that a mixed sediment profile will reflect more energy than both a sand beach (due to a steeper gradient) and a gravel beach (due to less energy dissipation through infiltration).

Threshold of Motion

The first order factors referred to above are concerned with the bulk properties of the sediment as a whole, but most physics-based equations of sediment transport employ a term to represent a critical or threshold fluid velocity above which the individual grains become mobilised. This term is generally related to sediment size, which makes it difficult to de-

scribe for a mixed sediment. Most of the sediment threshold experiments which have been carried out on mixtures of sediment sizes are for the sand fraction only and often for plane, horizontal beds under unidirectional flow, although the effect of bed slope on the threshold of motion is also of importance. In addition, establishing critical thresholds of motion for mixed sediments is complicated by the factors of "hiding" (relative protrusion into the flow), pivoting angle and angle of repose. There is some contradiction in the role of these processes. For example, some research suggests that larger clasts are entrained more easily due to their higher protrusion into the flow (FENTON and ABBOT, 1977; NADEN, 1987), whilst KOMAR and LI (1986) reported that granules within a mixed gravel-sized bed are removed first, since their critical threshold is lower.

The laboratory work of most relevance for mixed beaches is KUHNLE's (1994) study of the initiation of motion of bi-modal (sand and gravel) sediments, under unidirectional flow. The experiments were conducted on mixtures of 0, 10, 25, 45 and 100% gravel. For the 100% gravel samples, all sizes began to move at about the same reference bed shear stress. For all the mixtures, the sand fractions began to move at nearly the same shear stress, but for the gravel fractions the normalised bed shear stress was a function of grain size. For the 100% sand and all sand fractions of the mixtures, there was a -1:1 linear relationship between non-dimensional bed shear stress and relative grain size (D/D_{50}) as there was also for the 100% gravel sample, which indicates that each size within the fraction has near equal entrainment mobility. In contrast, the gravel fractions in bi-modal sediments retain some size dependence. Kuhnle speculated that the reason why the entrainment pattern of different sizes should vary was a result of the high percentage of sand. If there was over 50% sand, the interstices became filled with sand (the sediment was re-circulating in the chamber) but there was also a considerable amount of sand at the surface which could be entrained, much as would happen in a 100% sand sample.

Unfortunately, the sand:gravel mixtures used by Kuhnle are not entirely representative of the average proportions reported from mixed beaches, but he suggested that with a lower percentage of sand, the sand would become trapped within the interstices and not be available for transport, so that the effective transport rates of sand would be low (even at high flow velocities). Once the surface layer of sand is removed, the proportion of coarser grains exposed to the flow is increased and the near equal mobility of (coarser) sizes is restored, as suggested by PARKER and KLINGEMAN (1982). Accordingly, the coarsening process is inhibited in mixed beds, due to the high percentage of sand.

Of the remaining relevant laboratory work on thresholds of transport, EVANS and HARDISTY's (1989) laboratory experiments validated the slope-inclusive threshold model of DYER (1986) and reported that the threshold shear stress on a 15° slope (inclined upwards in the same direction as the flow) is between 40 and 89% higher than for a flat bed (depending on the type of rotation). It should be noted that the extensive review of sediment transport on sloping beds by DAMGAARD *et al.* (1995) identified only three further studies which spe-

cifically include gravel sized sediment (LUQUE and VAN BEEK, 1976; SMART, 1984 and CHIEW and PARKER, 1994).

There are very few field observations of gravel thresholds. Probably the most reliable report of field gravel/mixed sediment transport is from WALKER *et al.* (1991) where velocities through the inlet were measured when a mixed sand/gravel barrier in southern California was artificially breached for engineering purposes. They measured a threshold velocity of about 1.6 ms^{-1} for gravel of 5 to 200mm, with the whole range of sizes in transport together *i.e.* no preferential transport of differing sizes. Oscillatory velocities of this order have also been measured within the swash zone on a mixed/gravel beach during a field experiment undertaken within a recent UK Ministry of Agriculture, Fisheries and Food (MAFF) funded research project, managed by HR Wallingford (VAN WELLEN *et al.*, 1997; HR WALLINGFORD, 1999).

Second Order Factors

Clast Shape

This is an important control on sorting for coarse-grained sediments and therefore, theoretically, an initially homogeneous beach could translate into a stable shape/size sorted form. At the extremes, ORFORD (1975) maintained that discs have better suspension properties than spheres and therefore can be transported further landward by waves whilst spheres, being more pivotable, are preferentially entrained in backwash, thus accounting for the preponderance of discs to landward and spheres to seaward. ISLA and BUJALESKY (1993) considered that spherical particles are preferentially saltated over discs, plates and rods. KOMAR and LI'S (1986) experiments on uniform grain size beds found that shear stresses must increase progressively to entrain ellipsoidal, angular and imbricated clasts respectively, in comparison with spheres of a given size. Hence, imbrication is shown to resist entrainment and to be a particularly stable particle configuration.

BLUCK (1967) and ORFORD (1975) reported zonation of clasts based on their shape. Bluck derived two facies types, Sker and Newton, which he considered representative of high and lower energy environments respectively. ORFORD (1975) gave some support to these facies types, but argued that the facies type was not necessarily exclusive to any particular beach, but merely representative of the ambient energy conditions. Shape sorting tends to dominate when energy conditions are just sufficient to overcome thresholds of motion, but is less efficient in high-energy settings (WILLIAMS and CALDWELL, 1988) so that after storm wave activity no discrete zonation is found (ORFORD, 1975).

Tidal Range

This is also an important factor for shape sorting, particularly on macro-tidal beaches *e.g.* Shoreham, UK, where zonal sorting is less pronounced or organised. Even on a low-energy, micro-tidal beach, NORDSTROM and JACKSON (1993) observed that the rapid migration of the swash zone during the ebb tide reduced the time during which pebbles could be deposited at any one particular elevation of the profile.

Specific Gravity

In the only field study of transport rates of radically different sediments, MILLER (1997) found that sandstone particles travelled twice as fast as ironstone, whilst low density coal tracers were transported at 10 times faster. The sandstone was the naturally occurring sediment, whilst the coal and ironstone were industrial waste products. Given the notable difference in transport rates, particularly for the coal, variation in specific gravity is likely to be the cause, rather than particle shape or size differences. However, the existence of sediments with such a marked difference in specific gravity is likely to be of importance only locally and will depend on rates and type of sediment supply.

Armouring

The only field evidence for armouring on a beach is from ISLA (1993) who reported an armoured surface of gravel on macro-tidal, mixed sediment beach/barriers in Argentina. His conceptual model for this process concerned different types of movement for varying particle sizes during swash *e.g.* rolling of gravels, rocking motion of granules and fine gravels and kinetic sieving of sand. During backwash, inverse grading is the result of granules and fine gravels being more easily trapped than larger particles with greater inertia, so that at some stage, the finer particles have been deposited while larger pebbles are still rolling across them. These are classic overpassing conditions (EVERTS, 1973). However, Isla's sediment samples were at the surface and at depths of 0.04 and 0.1m, with the lowest sample regarded as representing the original deposit, yet erosion or deposition of 0.1m or more of sediment within a single tidal cycle is a common occurrence on mixed/gravel beaches, even in moderate wave conditions. In a saturated sediment, fluidization could occur, which could lead to sand particles being more easily entrained, whilst larger grains sink into the sediment *i.e.* in opposition to the process of kinetic sieving. In addition, it is also possible that the location of sub-surface sand merely represents the depth to which sand has been removed during the previous tide, so that the presence of more coarse sand at the lowest sample is not evidence in itself for the process of kinetic sieving.

Chemical processes

Possibly the only chemical process to affect mixed beach processes is the apparent "cementation" of replenished material, where the material dredged from offshore contains finer material derived from chalk sediments. Steep scarps of highly consolidated sediment have been observed on such replenished beaches (*e.g.* MCFARLAND *et al.*, 1996), but there has been no research into this.

MODELLING SEDIMENT TRANSPORT ON MIXED BEACHES

Ideally, a transport model would be applicable to a range of sediment distributions, integrating cross-shore and long-shore processes across the full transport zone, from outside the surf zone up to the run-up limit and would be able to accommodate the complexities of wave/current/sediment in-

teractions. This remains some way in the future. As yet, no existing gravel or sand models have been validated specifically for mixed beaches, either for bulk transport rates or for profile development. When the steep gravel beach extends into deep water, waves can approach close inshore before breaking (rather than breaking on the low gradient intertidal or low tide terrace), with the result that the breaker zone is concentrated over a narrow zone, with breakers usually of the plunging type. In addition, given the deeper water depths nearshore, in comparison with a sand beach, most wave refraction takes place close inshore, so that waves tend to break at more of an oblique angle than on a wide, sandy beach. Many sediment transport models are derived for sand transport primarily within the surf zone, where energy is dissipated by spilling breakers. Under these conditions, sediment transport is dominated by suspended load. In contrast, most gravel is transported as bedload, with swash zone processes increasing in importance relative to the surf zone. At present, it is in the swash zone where most wave transformation and sediment transport models remain under-developed (VAN WELLEN, 1999).

The foregoing might indicate that gravel sediment transport models should be more useful for predictions of transport on mixed beaches. At present, this is not necessarily the case since only a few equations have been developed even for long-shore sediment transport on coarse-grained beaches (e.g. VAN DER MEER, 1990; CHADWICK, 1991a; DAMGAARD and SOULSBY, 1996) most of which have involved some form of calibration from a very limited dataset (VAN WELLEN *et al.*, 2000). Few models contain the necessary components, even for simple gravel transport. For example, hydraulic conductivity is rarely incorporated into gravel models; even the force-balance model recently derived for gravel-sized sediment (DAMGAARD and SOULSBY, 1996) has yet to include the influence of infiltration on resultant net shear stresses on the sediment. The hydraulic conductivity of mixed beaches is overwhelmingly dominated by the sand content, which suggests that existing gravel transport models will be appropriate only when they are able to consider differential hydraulic conductivity.

Many sediment transport models include a term to represent sediment size, but almost invariably this is a single term such as D_{50} . This may be adequate for sand beaches where the difference in hydraulic properties between $200\mu\text{m}$ and $300\mu\text{m}$ sediment may not be of much importance. However, for mixed sediment beaches neither the D_{50} nor even a standard measure of grading (D_{84}/D_{16}) are likely to be suitable representative parameters for the hydraulic behaviour of the bulk sediment and, in any case, a gravel beach transport model which can include fractionation (where different sediment populations are modelled independently and then recombined to give total transport) remains to be developed. In addition, the D_{50} of the sediment is an inadequate representation of the hydraulic conductivity of the bulk sediment, although the grading might be sufficient.

As yet, no sediment transport model has been coupled to a groundwater flow model, even for sand beaches, despite the increasing realisation of the importance of fluctuations of beach groundwater to swash zone sediment transport. A model which was derived to predict tidally-observed fluctuations

of beach groundwater on sand beaches (BAIRD *et al.*, 1996) also predicted well the observed groundwater behaviour on a mixed beach, using a single value for hydraulic conductivity (MASON *et al.*, 1997). The model has been developed subsequently to include groundwater fluctuations due to set-up (BAIRD *et al.*, 1997) and the inclusion of swash is in progress. It remains the only beach groundwater model which has been tested for mixed sediments.

Potential Model Developments

Physically-based sediment transport models ultimately need to incorporate differential transport for grains of different sizes. Kuhnle's experiments (referred to above) validated the bi-modality parameter developed by WILCOCK (1993) to predict when mixed beds will be entrained in a different manner from uni-modal beds. This, in turn, can combine with the fractionation method of WILCOCK (1992), based on PARKER *et al.* (1982) which estimates the reference bed shear stress for each fraction necessary to produce a small amount of transport.

A vital ingredient for gravel/mixed sediment beach modelling is a swash/backwash module and there are several recent developments. ELFRINK and FREDSOE (1993) modelled swash and backwash flow on an impermeable but hydraulically rough bed, including the effect of turbulent flow in the wave boundary layer. They concluded that flow velocity and bed shear stress are reduced in the backwash (and increasingly so for higher bed roughness) due to an increase in depth of the boundary layer. Nonetheless, it is interesting to note that the predicted maximum backwash velocities were still of the order of 1 ms^{-1} and, combined with reduced critical shear stress for downslope mobilisation of sediment during backwash, it is probable that most mixed sediment sizes would be in motion at some stage of the backwash flow.

CHADWICK's (1991a, b) dynamic sediment transport model was derived specifically for bedload transport. It uses a hydrodynamic, phase resolving model based on the non-linear shallow water wave equations, coupled to a sediment transport model based on Bagnold's stream power concept as extended by MCDOWELL (1989). This model explicitly determines the swash zone hydrodynamics and, due to its phase resolving capacity, can predict bedload sediment transport within a wave period across the surf and swash zones. At present, the model has been validated against field data from a gravel beach for longshore transport only *i.e.* not for cross-shore transport and currently does not include any interaction with groundwater flow. However, developments are underway to extend the model to include the effects of porosity and fractionation (CHADWICK, *pers. comm.*).

A further potential base hydrodynamic model from which to develop a mixed beach transport model is that of DODD (1998) where the wave run-up and overtopping model includes the complex processes within the swash zone. Future developments of this model will include permeable slopes (DODD, *pers. comm.*). Other sources of useful hydrodynamic input are the numerical models for porous breakwaters (which include the loss of energy through infiltration) to establish energy/dissipation losses through non-Darcian flow

and, to some extent, for examining the effect of frequency dependent reflection from steep gradients. However they cannot, by definition, include frictional losses of energy by moving sediment.

RECENT FIELD AND LABORATORY STUDIES

Field Experiments

Since the last review of research on mixed beaches (KIRK, 1980), fieldwork has been patchy. The extensive series of papers by Orford, Carter and co-authors (*e.g.* CARTER *et al.*, 1990b; FORBES *et al.*, 1995 and many others) has maintained a geomorphological interest but, in general, the difficulty in deploying instrumentation on mixed/gravel beaches has meant that most research has concentrated upon the sediment and profile changes, inferring evolutionary and dynamic behaviour directly from sediment characteristics and sorting processes (*e.g.* CALDWELL and WILLIAMS, 1985; HILL, 1990; BUJALESKY and GONZÁLEZ-BONORINO, 1991).

Most field evidence suggests that the majority of transport on mixed beaches takes place in the inner surf/swash zone (*e.g.* KIRK, 1969; 1980). WALKER *et al.* (1991) also observed mixed size gravel transport confined to the uprush and backwash, rather than by longshore currents. The result was that the longshore transport rate for the gravel was less than 1 or 2% of the mean longshore current, indicating that the transport rates for the sand and gravel were effectively decoupled (no net longshore gravel movement, yet sand was transported southwards). However, these field observations are in contrast to measurements from a physical model of the cross-shore distribution of transport, which found that about 80% of longshore transport in higher energy conditions occurred in the narrow breaker zone (COATES and LOWE, 1993).

WALKER *et al.* (1991) reported probably the most important fieldwork to date on mixed beaches, in terms of process studies. Their findings were that:

- there was no preferential initial movement of clasts of different sizes
- critical threshold for movement was approximately 1.6 ms⁻¹ in water 0.2 to 0.3m deep
- there was a rapid increase in transport at a velocity of 1.7 ms⁻¹.

They noted also that almost all the longshore transport occurred within the swash zone, as a result of oblique transport in the swash and shore-normal backwash transport; there was practically no transport by longshore currents. All other factors being equal, the gravel transport increased as the tide range increased (from approximately 1m to 2m). They observed that the reduced backwash towards the top of the gravel bank (due to the increase in hydraulic conductivity) led to net deposition.

The only other field study of concurrent transport of bimodal sediment fractions is that of MILLER (1997) who used fluorescent sand and pebble tracers to examine differential transport rates at an unusual mixed sediment site at Weymss Beach in Fife, Scotland. She found that different fractions could be transported in different directions and at different rates. Under low energy conditions, sand was mobile whilst the pebbles were not, leading to their becoming buried. Under

higher energy conditions, pebbles were mobilised and transported in the direction of the dominant waves. Overpassing was generally confined to cross-shore transport. As wave height increased, sand was transported offshore and longshore transport of the exposed gravel increased. In general, the rate of longshore transport was lower when a high proportion of sand was present. Miller concluded that higher sand content increased the stability of the beach. However, it is possible that the low energy conditions were merely sufficient to initiate motion of the sand fraction only and that the critical thresholds for the finer gravel fraction were not met. BRAMPTON and MOTYKA (1987) suggested that $H_s = 0.5\text{m}$ could be considered a threshold for longshore transport of gravel. Under higher energy conditions, it is inevitable that the sand fraction will be removed (given its lower critical shear stress even when in mixed beds), the gravel fraction becomes near equally mobile and transport rates will be clearly related to the wave energy. It is likely that the sand will be transported in suspension in the offshore direction, due to net offshore currents and possibly due to any long wave energy present, which tends to transport sediment in a net offshore direction in the surf zone. In effect, the fact that the longshore transport rate was lower when a higher proportion of sand was present is a consequence of the energy conditions. Accordingly, Miller's observations may be an example of the de-coupled transport systems described by WALKER *et al.* (1991), rather than illustrative of a predictive process, based on sediment composition.

Fieldwork on a low energy, estuarine, micro-tidal beach led to a conceptual model for the distribution of surface gravel particles on a sand beach (NORDSTROM and JACKSON, 1993). The model predicts offshore transport of both sand and gravel during higher energy conditions, with subsequent burial of surface pebbles just above the low tide terrace. Fines are subsequently removed by exfiltrating groundwater at low tide, and in the post-storm recovery phase with low energy conditions, sand is preferentially transported landwards, leaving a lag of surface gravels near the low tide terrace. However, this model is not of obvious applicability to the mixed beaches of UK, since the gravel component forms only a small sub-population. NORDSTROM (1992) reported a tendency for coarser sediments lower on the foreshore, as found also by ISLA (1993), which is in direct contrast to the finer sediment found to seawards on open coast profiles.

PONTEE (1996) examined the profile response and sedimentary characteristics along the Suffolk coast, with observations over a variety of time scales namely, individual waves, single tidal cycles, spring-neap cycles, seasonally and longer term erosional/accretional trends. Generally, eroding beaches were steeper and narrower than the accreting beach, as previously observed by NICHOLLS (1985). Pontee's novel techniques included photo-sieving and the use of ground penetrating radar to discriminate sub-surface sediment layers. Details of the beach stratification could be of particular use in identifying the depth to near-impermeable layers, although at present the technique is restricted to regions above the water table.

Overall, field experiments have not provided any general agreement on the link between wave conditions/exposure and



Figure 3. Section through Lancing Beach, West Sussex, UK.

sand content, the proportion of which can change markedly. MCKAY and TERICH (1992) found that the proportion of sand generally reduced during winter months (though with notable exceptions) due to offshore transport of sand during storms. In contrast, PONTEE (1996) tentatively concluded that increasing wave height and period increased the sand content, although he found a great variability in sediment composition over a range of time scales (from days to months), under what were seemingly similar wave conditions. This highlights a major problem with determining which short-term processes are important on mixed beaches, since conclusions have generally been inferred from changes in beach profile and grain size analysis, without concurrent high frequency hydrodynamic data. For example, PONTEE (1996) and MILLER (1997) used visual wave measurements only. Inevitably, any contribution to the wave field from swell or longer period waves is likely to have been missed, yet is increasingly recognised as a formative factor in beach profile response (e.g. COATES and HAWKES, 1998).

A field study at a natural, composite mixed beach site at Morfa Dyffryn, concluded that the steep beach slope exerted greater control on the hydrodynamics (through increased swell wave reflection) than did energy dissipation through infiltration, since the sand content dominated the groundwater behaviour. Hence, the major significance of the sand/gravel mixture was in the maintenance of a steeper beach slope than would be achieved by a beach consisting purely of sand (MASON, 1997).

A new source of research data is the MAFF Shingle Beach Project which aimed to refine and develop models of gravel sediment transport (VAN WELLEN *et al.*, 1997, 1998). An extensive field database was compiled² which is particularly suitable for mixed beach investigations, since significant quantities of sand were present both laterally and vertically through the beach (Figure 3).

Laboratory Experiments

There are only three reports of laboratory studies on mixed sediment beaches. Two were concerned with profile development (QUICK and DYKSTERHUIS, 1994; HOLMES *et al.*, 1996) although the latter was for mixed sands only; the third examined 3-D hydraulically-induced sorting of mixed sand and gravel sediments *i.e.* cross-shore, alongshore and vertically through the beach (PETROV, 1989). Petrov's experiments began with an initially well mixed sediment composed of various fractions of coarse sand, fine and medium gravel, giving an overall D_{50} of just over 5mm at a nominal scale of 1:25. Still Water Level remained constant, and the waves approached at an angle of 15°. Hydrodynamic sorting resulted in a concentration of coarse material near the breaker zone and on the berm towards the wave run-up limit. The more spherical particles were transported seawards, whilst the

² The database is now in the public domain and is available on application to the second-named author, at HR Wallingford.

flatter particles moved landwards; this shape sorting is in agreement with the field observations of ORFORD (1975). Meanwhile, the sand fraction was removed from the surface sediments, both by transport alongshore and by sinking into the sediments below, producing an immobile layer of finer size fractions. Petrov attributed the downwards translation of smaller particles to kinetic sieving induced by wave action, although it might just as well result from simple downwashing by infiltrating water. His findings are entirely representative of the nature of sediment distribution found on a mixed beach. Unfortunately, there is no real predictive capability from these experiments, since only one sediment mixture was used, but they illustrate the formation of a mobile, coarser layer (which makes up the bulk of the material transported along shore) above an immobile layer consisting primarily of sands.

QUICK and DYKSTERHUIS (1994) studied the profile response of sand ($D_{50} = 900\mu\text{m}$), fine gravel ($D_{50} = 3.4\text{mm}$) and a 50:50 mixture, each of which was subjected to low, medium and high energy conditions in a small, regular wave flume (approx. 1:40 scale). The initial profile was steeper than the anticipated equilibrium profile. For the sand beach, all wave conditions led to offshore transport and lowering of the profile, increasingly so for higher energy conditions. For the gravel beach (which began with near-equilibrium slope), they established a threshold minimum wave height below which there was no transport. Above the threshold wave height, there was always some onshore transport, but a small gravel bar formed offshore, just to seaward of the breakpoint. Even the highest waves produced only a minor reduction in slope angle.

The response of the 50:50 mixed sediment profile was that the gravel did not move onshore, but some offshore transport occurred, so that the profile remained steep. Under medium wave attack, the gravel still tended to resist onshore movement, but some moved offshore to form a bar, so that the slope was reduced slightly. Under high energy conditions, strong offshore transport of both sand and gravel occurred and the profile resembled that of the sand beach under similar wave conditions *i.e.* it behaved in quite a different manner to the wholly gravel beach. It is particularly interesting that essentially the same behaviour was observed when the sand content was only 25%. QUICK and DYKSTERHUIS (1994) concluded that the sand is clearly the controlling factor for beach steepness and attribute the cause to the hydraulic conductivity. The profile change is achieved through the effect of infiltration, bed roughness and wave height. When combined with equations derived in QUICK (1991), they produced an analytical equation which takes an existing profile, a wave height and two sediment parameters (D_{60} and D_{10}) and predicts a new equilibrium profile.

The HOLMES *et al.* (1996) laboratory experiments on bimodal sand beaches using random waves are included in this review, since their conclusions have some relevance. Three beach profiles were tested, each consisting of medium sand ($D_{50} = 500\mu\text{m}$), coarse sand ($D_{50} = 1.5\text{mm}$) and 50:50 fine and coarse sand. The coarse sand beach incurred predominantly onshore transport with formation of a berm, whilst the fine sand beach suffered erosion leading to development of an

offshore bar. Interestingly, under the shortest period and steepest waves, the development of the berm appeared to be more rapid and its position more stable than that of the offshore bar, which continued to migrate seawards at a steady rate throughout the experiment. For the longer, less steep waves, the coarse sand berm was wider and higher, with more pronounced and continued development through the experimental run. This case also produced some onshore transport of fine sand, but most of the sediment eroded around the shoreline was transported offshore. HOLMES *et al.* concluded that:

- coarse sand within a mixed bed is more mobile than when part of a uni-modal sediment, consistent with a reduced angle of repose, greater exposure to the flow and reduced friction of a large grain on a smaller grained bed (MILLER and BYRNE, 1966)
- a mixed sand profile response is similar to that of a fine sand profile, therefore hydraulic conductivity of the sediment seems to be the controlling factor
- since hydraulic conductivity is determined by the finer fractions, addition of coarser material to a mixed sediment is unlikely to increase the stability of the beach.

HOLMES *et al.*'s findings on sediment sorting of bi-modal sediments are of interest, although they are difficult to extrapolate to mixed sand/gravel beaches, since only sand sediments were considered. It would be worthwhile to repeat their tests using other proportions of sediment mix *e.g.* 25:75 and 75:25 fine:coarse sand and to include sand:gravel mixes. In addition, tidal changes were not simulated, with the result that the influence of groundwater tidal asymmetry is not taken into account. This is of importance on macro-tidal beaches, since the pressure gradients within the sediment may be different between the flood and ebb phases of the tidal cycle, due to the tidally-induced super-elevation of the water table.

FUTURE RESEARCH

Given the operational difficulties and lack of environmental control during field studies on mixed beaches, the way ahead to understand their sediment transport processes, particularly beach profile response, lies in physical modelling. However, a major drawback to physical modelling is the problem of scaling; it is impossible to scale mixed sediments for correct hydrodynamic response and representative hydraulic conductivity. This well-documented problem of scaling (*e.g.* BRAMPTON and MOTYKA 1987; LOVELESS *et al.*, 1996) effectively confines future physical modelling to one of the few near-prototype (1:1) scale flumes. It is important also that any laboratory sediment should be of sufficient depth to simulate correctly the patterns of groundwater flow through the sediment. For example, LARSEN and SUNAMURA (1993) determined the flow patterns of both swash and backwash across a beach step on a relatively steep profile of coarse sand using flow visualisation techniques; such a step typically develops on a gravel beach and migrates cross-shore with the tide. However, no mention was made by LARSEN and SUNAMURA (1993) of any loss of water volume by percolation, despite an attempt to represent the correct groundwater circulation by using 0.1m depth of sediment. It is possible,

therefore, that the depth of sediment was insufficient to represent the naturally occurring drainage patterns of a coarse sand beach. This is a serious drawback which hampers all small scale laboratory studies *e.g.* the effective depth to the impermeable barrier was 30cm below SWL for PETROV (1989), seemingly less for QUICK and DYKSTERHUIS (1994)'s experiments.

Use of a large scale facility would permit physical models representative of the vertical sediment composition found on natural beaches. The importance of this was suggested by the mobile bed flume study of POWELL (1990), who included tests with an impermeable layer on a gravel beach. For a gravel depth $> 100 D_{50}$, the impermeable layer had no influence, while gravel depth $< 50 D_{50}$ resulted in a significant increase in erosion. Field observations from COATES and BONA (1997) appear to support these conclusions.

Smaller scale wave flumes can be used to investigate upper beach processes such as infiltration/exfiltration, run-up and berm formation; by generating long period waves and concentrating on processes above the still water line, such flumes can be used to provide valuable information for numerical model development. However, they cannot replace large scale experiments.

From an engineering perspective, there is an urgent need for information about the performance of recharge schemes using mixed sediments, preferably by comparing the pre- and post-scheme beach behaviour. Changes in sediment distribution and beach profiles over time, sediment budgets, management operations, storm responses and the impact of structures will all be useful to the development of a greater understanding of processes. Rigorous comparisons of performance against design predictions will be important to determine the weaknesses in existing predictive approaches. Ultimately, the longer term wave climate/beach profile/sediment composition monitoring must be synthesized with detailed, short-term process studies to answer the most pressing of beach replenishment questions:

Given a sediment source of X grading, how will the beach respond to a given wave climate?

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