CHAPTER 142

CHARACTERISTICS OF SHINGLE BEACHES WITH REFERENCE TO CHRISTCHURCH BAY, S. ENGLAND

by Robert Nicholls* and Norman Webber+

ABSTRACT

The rapid recession of the shingle bank of Hurst Beach (up to 3.5m/yr) makes it an excellent natural laboratory for the study of the factors which influence the stability of shingle beaches. Studies have included: the significance of long period, high energy, swell waves - the classification and quantification of overwash processes - run-up and seepage characteristics - the effect of settlement of the underlying strata - and the implications for practices in shingle nourishment. The studies have revealed the distinctive character of shingle beaches as compared with the more fully researched sand beaches. More detailed research on shingle beaches is justified particularly in relation to (i) the run-up characteristics including its interaction with swash cusps and (ii) the influence of the subsidiary sand fraction on the beach characteristics.

INTRODUCTION

Pebble and cobble (henceforth called shingle) beaches, or at least beaches where the upper foreshore is predominantly shingle, are to be found in many parts of the world, but are nowhere of more coastal engineering significance than in Britain (Carr, 1983a). Whilst for recreational activities such beaches have less appeal than their sand counterparts, they are nonetheless one of the most efficient forms of coast protection.

In Southern and Eastern Britain, maintenance usually entails regular profile monitoring and, when needed, the construction of groynes and the recycling of shingle transported by littoral drift (e.g. Foxley & Shave, 1983). Projects involving shingle nourishment, usually from marine sources, are becoming increasingly favoured (e.g. Hayling Island, Hampshire and Seaford, Sussex).. This has raised important questions concerning the field characteristics of shingle beaches. The extensive literature on sand beaches is often misleading when applied to shingle beaches because of fac-

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tors such as permeability (e.g. Muir-Wood, 1970).

The authors have over a number of years examined the processes operating on Hurst Beach, the shingle bank at the eastern end of Christchurch Bay between Saltgrass Lane and Hurst Castle (Fig. 1). Hurst Beach is being starved of littoral drift due to updrift coast protection works, comprising seawall and groynes at Milford-on-Sea and recently has experienced rapid recession of up to 3.5m/yr. (Nicholls & Webber, 1987a; 1987b). Thus, Hurst Beach makes an excellent natural laboratory where the processes which influence the stability of shingle beaches can be examined and quantified. Much of the work has been described in detail by Nicholls (1985). Some of the conclusions of pertinence to the stability of shingle beaches are summarised in this paper.

THE STUDY AREA

The beaches in the eastern half of Christchurch Bay (Fig. 1) are composed of shingle with a mean size in the range -2.5 to -5.5 phi (6 to 45mm) with subsidiary fine to coarse sand (125 to 1000μm) which mainly occurs on the foreshore. The form of the beach profiles on Hurst Beach are fairly typical of many of the shingle banks in southern Britain. The foreshore (average slope about 8°) is backed by a supratidal beach face (average slope about 11 to 13°) and a beach crest (Fig. 2). Landward of the crest the beach drops with a variable slope (typically 5 to 13°) to a saltmarsh. The crest height varies both temporally and spatially with a maximum elevation in the period 1980 to 1982 of 4.6m. O.D., 3.6m. above the highest predicted tide (O.D. approximates mean sea level). The net littoral drift is eastwards, but

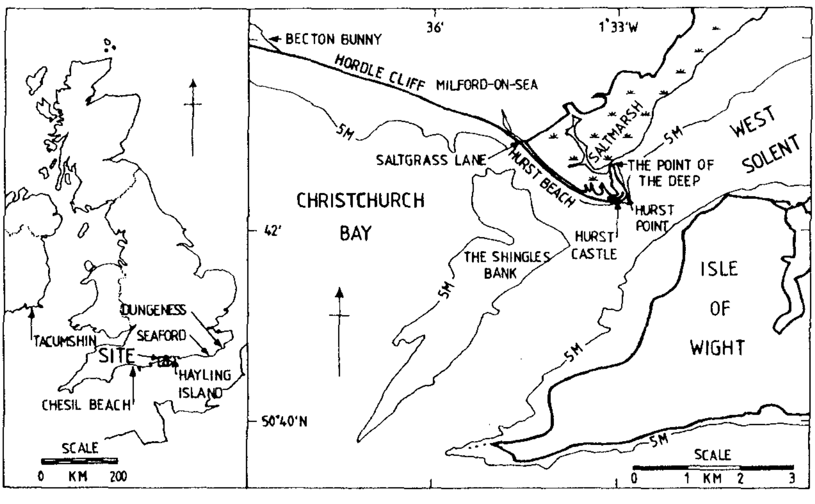

Fig. 1. Location Plan. Crown Copyright. Reproduced from Admiralty Chart 2219 with the permission of the Controller of Her Majesty's Stationery Office.

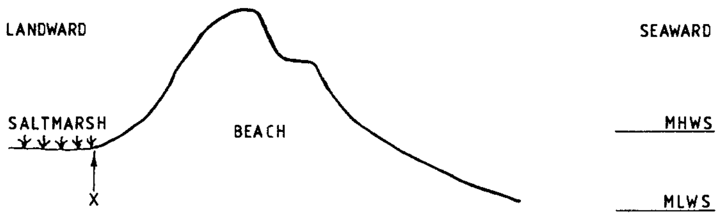

Fig. 2. A typical beach profile across Hurst Beach (vertical exaggeration X5)

with a sub-cell boundary (i.e. a minimum in the rate of net littoral drift) at Hordle Cliff, (Nicholls & Webber, 1987a).

The study area is exposed to waves generated in the Atlantic and the western English Channel. However, the Isle of Wight and the shallow shoal of the Shingles Bank, have a major effect on the energy and direction of waves impinging on the shoreline. In contrast to the British Isles generally, the tidal range is quite small, being 2.2m at springs. Storm surges can add up to 1m to water levels in this part of the English Channel. This means that, even during a neap tide, the highest predicted tide (HAT: 1.05m O.D.) may be exceeded. There are fast tidal currents off Hurst Castle in the narrow entrance to the West Solent, attaining a maximum of 2.3m/s. on mean spring tides.

LONG PERIOD WAVES

Long period, high energy swell waves originating in the Atlantic have caused significant overwashing of Hurst Beach on at least two occasions, 13 February 1979 and 2 January 1986. Both events coincided with a surge in the English Channel raising high water at Hurst Point to 1.4 and 1.0m. O.D., respectively. In February 1979, a high energy swell (H_s = 7m, T_z = 18s) entered the English Channel from the Atlantic and caused considerable coastal damage, notably at Chesil Beach (Draper & Bownass, 1983). In Christchurch Bay the swell ($H_s \leq$ 2.5m) caused significant overwashing of Hurst Beach and it appears that the recession of the landward margin (X in Fig. 2) was locally as much as 60m (Nicholls, 1985). In January 1986, swell waves again caused overwashing of both Chesil Beach (Dobbie & Partners, 1986) and Hurst Beach, although the damage was less severe. The energy spectrum from West Bexington (at the western end of Chesil Beach) at the height of the event shows energy present over a wide range of wave periods, with a main peak at 16 seconds and a secondary peak at 9 seconds, corresponding to locally generated waves. (Fig. 3). Two wave periods were also apparent in visual wave observations at Hurst Beach (H_b = 2m, T = 9 and 25s). The overwashing was evidently due to the longer waves. These two events are considered in more detail in subsequent sections.

Clearly, swell waves are an important factor when considering the stability of Hurst Beach. Indeed, when combined with a surge, they may, like Chesil Beach (Carr, 1983b) produce the greatest run-ups and this situation may apply generally wherever beaches are exposed to long fetches.

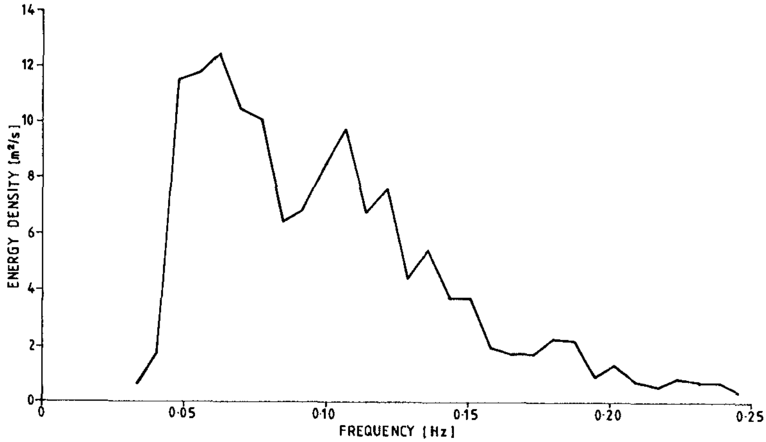

Fig. 3. The energy spectrum at West Bexington at 1030 GMT on 2 January 1986. (Measured by the Institute of Oceanographic Sciences).

OVERWASH PROCESSES

Overwash is defined as any swash that passes over the highest point of a barrier beach, which in the case of a shingle bank is the crest. Thus, overwashing causes sediment transport from the seaward to the landward side of the barrier. Overwash processes have received most attention on the sandy barrier islands of the East and Gulf Coasts of the USA (e.g. Leatherman, 1979; Oertel & Leatherman, 1985), but are also of importance on mixed sand and shingle barriers (Orford & Carter, 1982) and shingle banks. For instance the landward recession of Hurst Beach is caused by overwashing (Nicholls & Webber, 1987b) and a number of washover fans (the product of overwashing) can be seen on its landward margin. In Britain, such processes have often been described as 'overtopping' but it is best if this term is only used to describe processes which increase the height of the crest (cf Orford & Carter, 1982). Thus, overwashing may be seen as the 'failure' of a shingle bank.

On Hurst Beach two distinct forms of overwashing can be distinguished:

(i) Crest-maintaining overwashing. The overwashing occurs without the height of the crest being reduced, e.g. Fig. 4 (small changes in the height of the crest of about 0.1m may occur);

(ii) Throat-confined overwashing. The overwashing locally reduces the height of the crest to form what is usually termed a 'throat' or occupies a pre-existing topographic low. A washover fan is deposited on the landward side of the throat.

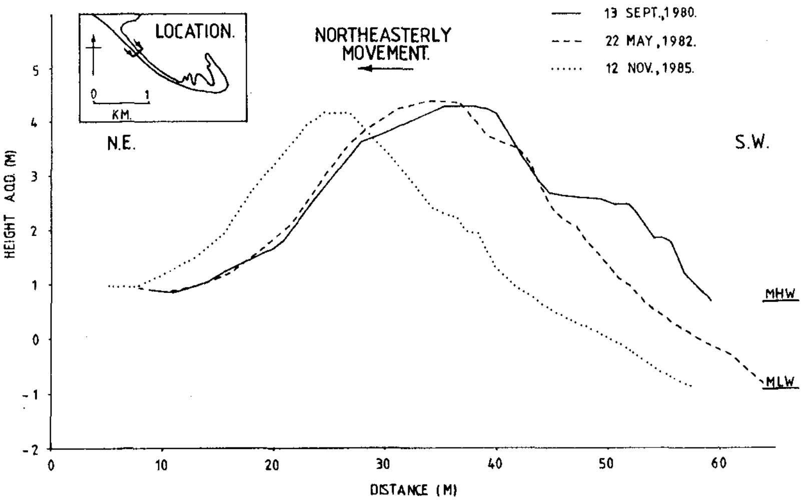

Fig. 4. Recession of a sample cross-section of Hurst Beach due to a series of crest-maintaining overwashing events (after Nicholls & Webber, 1987b).

Only the latter process has been described on sand barriers (e.g. Leatherman, 1979) or the mixed sand and shingle barriers of SE Ireland (Orford & Carter, 1982). The occurrence of crest-maintaining overwashing on shingle beaches is attributed largely to their high surface permeability. These two forms of overwashing may occur simultaneously at different locations (Fig. 5) and are clearly related: as the volume of swash passing over the crest increases so does the likelihood of the crest being reduced in height, causing a transition from crest-maintaining to throat-confined overwashing. The surface permeability must also be of significance in this transition. An extension of throat-confined overwashing to more widespread failures of the crest occurred on 23 November 1984, but individual throats were still present within the low sections of beach (see below).

On Hurst Beach, overwashing is most frequent at Saltgrass Lane, where the beach is most depleted. Throat-confined overwashing occurred on about 6 occasions per year between 1980 and 1982. More recently, shingle nourishment has reduced its occurrence. Elsewhere, overwashing occurred about twice a year between 1981 and 1987, although not all the beach was affected in any one event. Overwashing usually occurs in response to storm waves combined with a surge, such that the tidal elevation approaches or exceeds the highest astronomical tide (1.05m O.D.). Two important exceptions are the overwashing of Hurst Beach by large swell waves, on 13 February 1979 and 2 January 1986, (see previously). Several large washover fans thought to have been deposited by throat-confined overwashing during the former event were still present on the back of Hurst Beach in May 1988.

Fig. 5. Well-developed active regularly-spaced washover throats (A, B and C) on Hurst Beach on 2 January 1986. Crest-maintaining overwashing is occurring on the left of the picture (X).

Crest-maintaining overwashing is by far the more common process. Between 1980 and 1984, with the exception of three throats, all throat-confined overwashing occurred at Saltgrass Lane. However, on 23 November 1984, there was significant storm wave activity accompanied by a surge raising tidal levels to an estimated height of 1.6m O.D. The crest was reduced in height over a total distance of about 350m, comprising two lows containing 7 and 9 throats, respectively (Fig. 6).

Every throat formed in the period being considered was filled artificially in an attempt to reduce recession, usually using the washover deposits. Therefore, the long term evolution of the throats was not observed.

Crest-maintaining overwashing is a less efficient mechanism for net onshore sediment transport than throat-confined overwashing: the maximum measured volume of onshore transport over the crest during a single storm was 6m^3/m as compared to 150m^3/m due to throat-confined overwashing. An overwash budget for Hurst Beach is not available, but it is clear that infrequent throat-confined overwashing events could equal or exceed the net onshore transport caused by more numerous crest-maintaining overwash events.

Therefore it is worth considering if the prevention of overwashing should always be a principal aim in shingle beach management. Throat-confined overwashing is clearly unacceptable. In contrast, the shingle bank remains an effective barrier during crest-maintaining overwashing. Very few, if any, swashes reach the landward margin. The resulting landward movement of the bank is easily monitored, although as Fig. 4 illustrates, it can be quite rapid (3m/yr). The main benefit is the smaller volume of beach fill required. This approach may be useful as a short or medium term solution to problems at sites where some recession is permissible.

RUN-UP CHARACTERISTICS

Although no direct run-up measurements were made, the formation of washover throats on a beach with a uniform longshore section allows the position of a run-up maxima to be inferred. The run-up associated with these high energy events is of most interest in studies of coastal stability.

The spacings of the washover fans and overtop deposits formed on 23 November 1984 are shown in Fig. 6. In the case of the overtop deposits, the longshore peaks of run-up were indicated by a topographic maximum where vertical accretion had been most pronounced, rather than a topographic minimum as indicated by the throats (Fig. 6B). The sample comprises 27 measurements with a range between 10.3 and 45.7m. The distribution is approximately lognormal. The washover throats show two distinct modes at about 13 and 23m with a few larger spacings. The overtop deposit data is more scattered with the mode occurring at about 19m. The scatter is to be expected as the overtop deposits have a volume a tenth or less than the washover throats and as such will not 'record' the run-ups so clearly. Taking the dataset as a whole, there is a significant (sig. > 95%) decline in the spacings along Hurst Beach (Fig. 6C). The interpretation of this result is not clear. Not surprisingly, taking the scatter and this factor into account, autocorrelation showed no significant evidence of memory. However, when the results were compared with a Poisson distribution for longshore spacings of 10, 15 and 20m, the observed distribution was non-random in all cases (sig > 95%). Thus, the washover throats and overtop deposits show a preferred longshore spacing, but cannot be considered to be periodic.

On 2 January 1986 the throat-confined overwashing of Hurst Beach by the long period swell produced four small throats with a regular longshore spacing (mean = 37m, standard deviation = 2.69m) (Fig. 5). The adjacent crest-maintaining overwashing showed similar longshore spacing, although it was not possible to take direct measurements. This observation indicates that the run-up was exhibiting regularly-spaced maxima along the shore.

Thus two distinct overwash events of Hurst Beach have produced morphological evidence indicating non-randomly spaced longshore maxima of run-up. Orford & Carter (1984) have described over 60 regularly-spaced washover throats on the mixed sand and shingle barrier of Tacumshin, S.E. Ireland. The modal spacing was about 40m and appeared to be contolled by high elevation beach cusps.

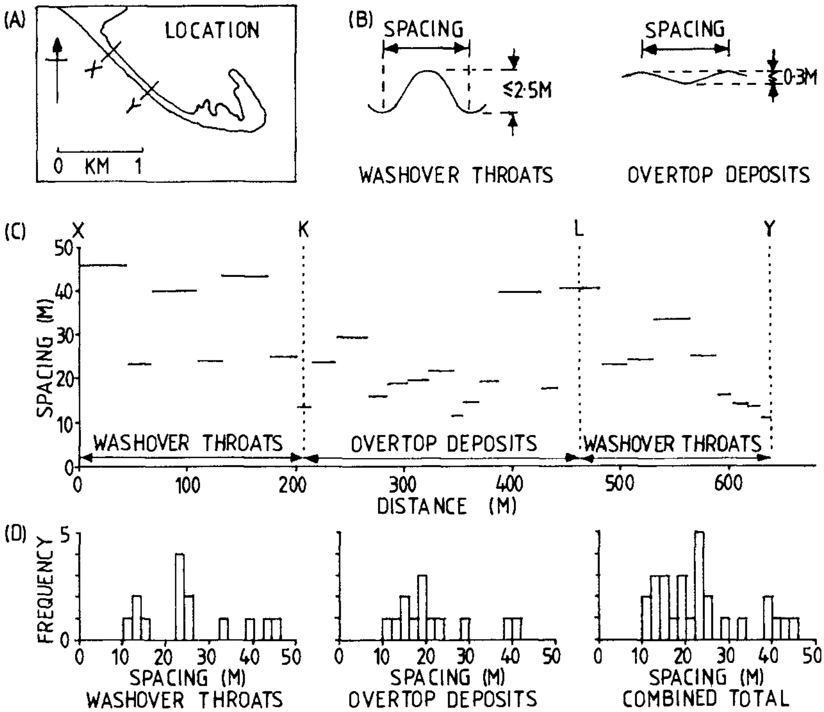

Fig. 6. The longshore spacing of the washover throats and overtop deposits formed on 23 November 1984. (A) Location Plan. (B) Definition sketches of spacing as measured on washover throats and overtop deposits. (C) The location of each longshore spacing between X and Y together with its magnitude. Spacings K and L are transitional between the two morphologies. (D) The numerical frequency distribution of the washover throats, the overtop deposits and their combined total.

Two distinct hypotheses may explain regularly-spaced run-up maxima:

(i) longshore variation in the wave field e.g. phase-coupled edge waves;

(ii) interaction of the run-up with pre-existing rhythmic three-dimensional beach morphology e.g. run-up amplification at swash cusps.

To some extent these two hypotheses are linked as it is generally considered that many three-dimensional beach features are a product of edge waves e.g. swash cusps (Inman & Guza, 1982). However, it is important to distinguish between active longshore variation in the wave field and the influence of three-dimensional morphology which may modify the run-up a considerable period of time after the waves which produced it have ceased.

Large swash cusps with a similar mean spacing (36.6m), but a larger standard deviation (7.38m) than the washover throats are known to have been present on Hurst Beach prior to 2 January 1986. During the overwashing the beach face showed a rhythmic undulation which was in phase with the active throats. These are presumed to have been the subdued remnants of the pre-existing beach cusps. A similar mechanism may have occurred on 23 November 1984, although no evidence is available. By contrast, active edge wave control appears unlikely. The most easily excited edge wave and the one with the largest amplitude is a zero mode subharmonic edge wave (Inman & Guza, 1982). Such an edge wave would have produced longshore run-up maxima with a spacing of about 44 (23 November 1984) and 112m (2 January 1986), showing little agreement with the field data. Thus it is inferred that run-up amplification at swash cusps can be of significance on shingle beaches. Orford & Carter (1984) favoured an active edge wave control of the throat spacings they observed in Ireland. However, the wave conditions which produced the throats are poorly known and a similar mechanism to that inferred for the two events at Hurst Beach is quite plausible.

These results all illustrate our poor understanding of run-up on coarse-grained beaches and yet the maximum run-up is one of the most important parameters required in the design of shingle nourishment schemes. The occurrence of run-up maxima suggests that the results of two-dimensional flume model studies may be inappropriate for studies of maximum run-up. Even in the absence of the evidence presented, the formation of a single washover throat on a previously uniform length of beach leads to the same conclusion. Clearly, wave basin model studies combined with accurate field measurement of run-up characteristics on shingle beaches are required, (see Holman & Guza, 1984). These should include an analysis of the longshore structure of run-up and its interaction with three-dimensional topography. From the evidence presented, it is apparent that even with a uniform incident run-up, amplification of that run-up at swash cusps may occur and this process requires quantification. The common occurrence of swash cusps on shingle beaches may make this a significant factor. The run-up characteristics of long period high energy swell waves must also be considered.

SEEPAGE CHARACTERISTICS

Shingle beaches are highly permeable when compared to their sand equivalents. The piezometric and seepage characteristics of Hurst Beach were investigated along one cross-section using a line of standpipes (Fig. 7).

The constriction of the tidal flow between Hurst Point and the Isle of Wight causes a differential water level of up to 0.7m across Hurst Beach on the rising stage of equinoxial tides, i.e. higher water levels in Christchurch Bay than in the West Solent. This might be expected to produce landward seepage of seawater through the beach. However, this is not the case, and the water table shows its maximum amplitude at the landward margin (see Day 2 - Fig. 7). This apparently anomalous behaviour can be mainly attributed to the large permeability contrast, estimated to be of the order of 10^3, between the relatively impermeable veneer of sand over the foreshore and the more permeable much less sandy washover deposits on the landward side. This example illustrates that while shingle beaches are highly permeable, the sedimentology, particularly the amount and location of sand, has a profound influence on the seepage characteristics of such beaches.

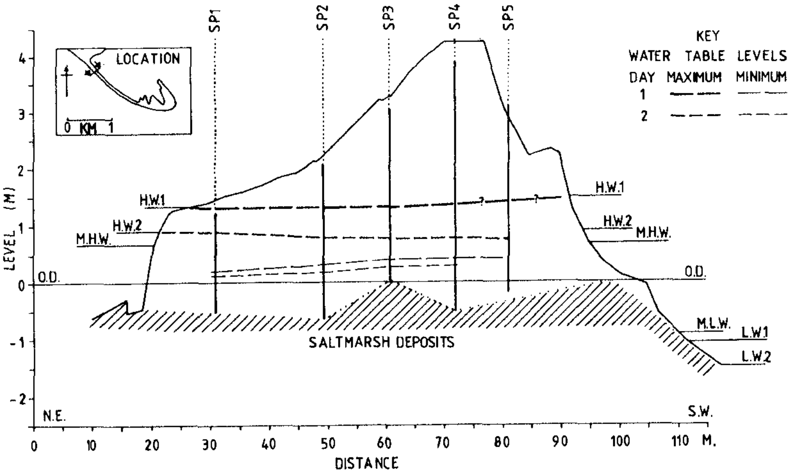

Fig. 7. Maximum and minimum water levels at five standpipes (SP1 to SP5) in Hurst Beach in response to an equinoxial tide and storm waves. (Day 1 - 8 March 1981) and an equinoxial tide and calm conditions (Day 2 - 5 April 1981). The elevation of high water for Day 1 in Christchurch Bay (on the south-west side) includes an estimate of wave set-up. The elevations of low water are estimated and only shown for guidance.

Landward seepage of seawater through the beach does occur, but only in association with wave activity. For instance on 8 March 1981, with breaking waves of up to 1.8m, the water table dipped landward throughout the tidal cycle (Fig. 7) with flows estimated to be in the range 0.3 to $1.7m^3/h/m$. The differing behaviour may be attributed to:

(a) Offshore sediment movement of the sand veneer on the foreshore exposing more permeable sediments;

(b) Increased differential water levels across the beach due to wave set-up, plus a contribution to the water table due to swash infiltration.

These effects are reinforced by high water levels produced by storm surges, because it appears that, in bulk terms, there is a vertical increase in the permeability of the beach.

Fig. 8. A seepage hollow formed on the landward side of Hurst Beach on 23 November 1984. Note the angle of repose slope. The man is 1.80m tall.

Between 1980 and 1986 the seepage of seawater through Hurst Beach was sufficient to cause local erosion of its landward margin on at least six occasions. This produces paired erosional seepage hollows and depositional fans (Fig. 8). Some of these occasions were significant storm surges but this was not always the case, wave height also being of importance. The elevation of some of the seepage hollows (up to 1.7m O.D.) demonstrates the high water levels which may be developed within the beach. These features display a wide range of morphology, some being similar, but on a smaller scale, to the so-called 'cans' of Chesil Beach (Carr & Blackley, 1974). The maximum volume of shingle eroded from a seepage hollow during a single storm was $10m^3$ (or about $5m^3/m$). Once formed a seepage hollow may be active again producing an increase in size. However, the rapid recession of Hurst Beach leads to the regular infilling of the seepage hollows with washover deposits.

A feature of all the seepage hollows observed was an angle of repose slope (e.g. Fig. 8). Shingle is removed from the base of the hollow resulting in a slope failure migrating into the beach. Clearly if this process were to continue until the seepage hollow intersected the crest it would result in failure of the beach, creating a site for throat-confined overwashing. The size distribution of the seepage hollows suggests that this did not happen on Hurst

Beach during the period of observation. However, at Dungeness, Kent (Eddison, 1983) and in S.E. Ireland (Carter, Johnston & Orford, 1984) seepage erosion appears to aid overwashing. On a nourished shingle bank which will usually be designed to be static, the attritional losses caused by seepage erosion could ultimately have similar consequences. Thus, any beach profiling/monitoring should include any landward slope in addition to the seaward portion of the beach.

SETTLEMENT BENEATH BEACHES

As Hurst Beach moves northeastwards, due to overwashing, so it is moving across the Spartina saltmarsh which occurs in its lee. Saltmarsh deposits can often be seen on the foreshore but are rapidly eroded. The best such exposure known to the authors occurred between 1979 and 1980 when several hundred square metres of former saltmarsh surface was clearly exposed, including the dead and crushed Spartina stems and leaves (Fig. 9). The surface was horizontal as in the living saltmarsh, but levelling demonstrated that it was about 1.0m lower. After careful examination of a number of hypotheses it was concluded that the difference in elevation was due to the settlement of the saltmarsh deposits beneath the weight of the beach. The Spartina surface of the saltmarsh provides a useful datum for the direct measurement of such changes.

Cartographic evidence demonstrates that the settlement must have occurred in less than 10 years. The thickness of the deposits behind the beach exceeds 5m and includes an unknown thickness of highly compressible peat. The thickness of the beach sediments shows both temporal and spatial variation with a probable maximum of 4m at this site. A preliminary geotechnical analysis demonstrates that the settlement will not have reached completion in 10 years, although there is some uncertainty about long-term values.

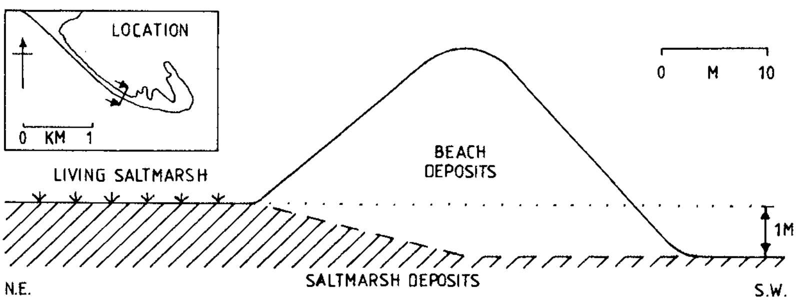

Fig. 9. A diagrammatic cross-section illustrating the settlement of the salt-marsh deposits which was visible across Hurst Beach between 1979 and 1980.

It is concluded that the geotechnical properties of the deposits beneath beaches may have significance when considering beach stability. This factor is independent of grain size and also applies to sand beaches (e.g. Dean, 1987). Rapid settlement will reduce the elevation of the overlying beach and thus on an eroding coastline will accentuate shoreline recession. In the static situation of nourishment, settlement must be considered when calculating volumes of beach fill. In effect, settlement provides a third potential loss of sediment in addition to offshore and longshore losses.

SHINGLE NOURISHMENT

In recent years, marine-dredged beach fill has become the dominant source for shingle nourishment in Britain on a tonnage basis. However, it normally contains considerable quantities of sand due to: (i) source and (ii) the method of delivery to the beach. Split bottom barges drop the dredged gravel as high on the foreshore as possible during the rising tide. On the falling tide the gravel is recovered and placed where required. This method inevitably mixes the sandy foreshore sediments with the beach fill which itself may contain finer material to assist pumping. Such mixtures of shingle and sand are rarely present on the supratidal portion of 'natural' shingle beaches, largely because they are eroded by waves. Thus, marine-dredged beach fill is usually unstable on the supratidal portion of a shingle beach. For instance, at Hurst Beach and Hayling Island marine-dredged beach fill was imported as described. During storms, offshore sediment movement occurred and vertical supratidal beach scarps, locally up to 2m high, developed. (Fig. 10). While subsequent onshore transport deposited shingle berms, the scarps persisted for months at both sites, migrating onshore during storms, before being removed artificially. At Hayling Island they reformed suggesting that they may persist for years without human interference.

Beach scarps up to 3m high are common features on some sandy beaches (Sherman & Nordstrom, 1985), but shingle will only support a vertical slope when sand fills the interstices, e.g. beach scarps up to 0.1m high have formed for short periods (hours) in the foreshore sediments of Hurst Beach. Thus, the scarps in the beach fill are an order of magnitude larger and much more persistent than any equivalent features on a natural shingle beach. Scarp formation was not observed, but clearly involves accentuated offshore sediment movement from the base. Once formed, the vertical scarp must cause wave reflection when active, accentuating offshore sediment transport in a similar manner to a seawall. This is not to say that the beach scarp is the primary cause of the erosion, it only being a response to the hydraulically unstable sediment distribution.

Therefore, it is best to use land-derived beach fill which usually contains little or no sand for shingle nourishment. However, the large scale of many recent and proposed nourishment schemes probably makes such sources inappropriate.

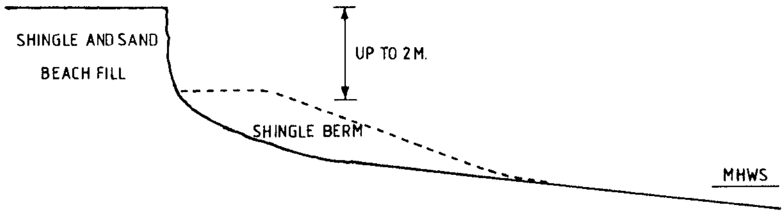

Fig. 10. A diagrammatic cross-section through a beach scarp on a nourished shingle beach.

Some improvements in marine delivery methods may be possible. If not, suitable allowance for beach scarping must be made during design. Assuming that the volume of beach fill is appropriate and longshore losses are small, in the long-term, scarping is not a problem; rather it should be seen as sorting of the beach fill. The shingle moved offshore is returned to the beach while the sand will remain on the foreshore and ultimately the beach will display a surface sorting similar to that seen on a 'natural' shingle beach.

CONCLUSIONS

Shingle beaches exhibit characteristics which are somewhat distinct from sand beaches. These include a far superior performance under wave action for equivalent volumes of beach material, so it is not surprising that shingle is becoming increasingly favoured as a nourishment material. However, field studies indicate a number of problems which require more research. Of particular importance is the observation that run-up shows longshore maxima. There is inadequate understanding of run-up on shingle beaches and its interaction with the swash cusps which are so often present. The role of the subsidiary sand component of the beach sediments is often ignored, but is of importance with regard to factors such as permeability and beach scarping. It is also important that existing shingle nourishment projects are monitored and studied.

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