CHAPTER 68

CHARACTERISTICS OF SHINGLE BEACHES
THE SOLUTION TO SOME PRACTICAL PROBLEMS

A. M. Muir Wood
Partner, Sir William Halcrow & Partners

ABSTRACT

Shingle beaches differ from sand beaches mainly in the mode of transport of the material and in the permeability of the beach. The typical beach forms are in consequence different and the typical problems of beach stabilisation require different types of solution.

The mechanism of littoral drift of shingle is controlled predominantly by the action of the breaking wave, on a groyned beach a simple theory is advanced to relate drift to groyne length and spacing.

Longitudinal sorting of shingle sizes is a specially notable sign of a stable beach. Well marked size-sorting transverse to the coastline is a more general characteristic.

Examples of schemes of management are provided for a beach with high littoral drift and a beach which has to be controlled as artificial cells

The accreting shingle beach may in suitable circumstances develop a steep in-shore profile - examples are given of such.

FORCES CONTROLLING THE BEACH PROFILE

The extensive literature on the engineering properties of a natural beach is principally concerned with fine to medium sand foreshores. In consequence, a number of generalisations have been made concerning the properties of a beach that do not apply, however, to a shingle or even to a coarse sand beach. The object of this paper is to discuss some of the properties specific to a shingle beach and briefly to describe solutions relevant to the typical problems that arise with them. By definition, a shingle beach is one in which the median particle size D_{50} is larger than 10mm. The mean size is most often in the range 10-40mm.

South-east Britain is well provided with natural shingle beaches and Fig. 1 illustrates a number of the lengths of coastline concerned. The main reason for the predominance here of shingle is that the principal constituent, flint pebbles, was originally formed in the massive chalk which has since been widely eroded over this area. Secondary fluvial and marine deposits have provided copious sources of flint (silica) which have been washed inshore as the sea level rose following the most recent glaciations. Once the flint pebbles become well rounded they tend to be reduced gradually in size by attrition rather than to be reduced to sand by fragmentation.

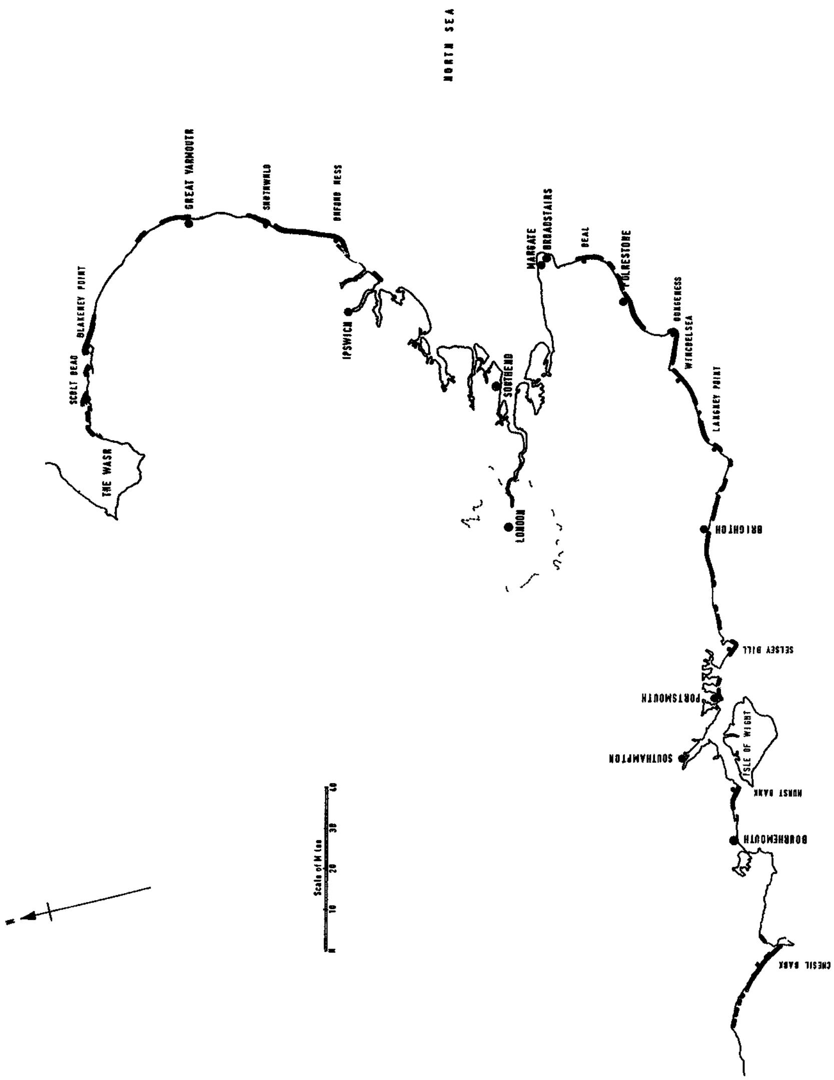


Fig 1 - PRINCIPAL SHINGLE BEACHES OF THE SOUTH AND EAST COAST OF BRITAIN

The main differences between the coastal behaviour of shingle and sand are relatsd to the mode of transport and to the permeability of the beach. Whereae eand is moved by the sea predominantly in saltation and, near and inshore of ths breaker line, in suspension, shingle is ehifted by sliding and rolling along the bottom. The significance of this difference is that, whereaa sand will tend to be moved in the direction of the vector representing reeidual wave velocity plus tidal velocity, shingle is only moved during that part of the wave velocity cycle in which a certain threshold value ie exceeded. Generally this threehold value will be little below maximum velocities at the situation and in consequence the direction of high velocity will greatly predominate In addition, the emount of work required to move ehingle on the eeabed in substantial quantitiee ie euch that this movement will generally be confined to areae of high rate of dissipation of wave energy, i e. landward of the breaker line. Shingle immediately to eeaward of this line, except whers the offshore bsd is steep, will tend to move ehoreward, if dieturbed at all, on account of the aeymmetrical shape of the wave lsading to higher ahoreward orbital vslocities.

The ehingle beach, with a typical slope of 1 10 or steeper, ie appreciably stseper than the equilibrium sand beaoh and this is largely due to the extent of percolation of the ewash of the breaking wave into the shingle beach, leading to a diminution of the downwash To treat this phenomenon in a very eimpls instance, we may consider the lower bound of ths velocity of steady percolation of water into a beach at gradient S to be $k/\frac{\pi}{2S}$ which is about 6om/s for a typical value of permeability, k, of 10^2cm/e for a beach at 1 10 slope.

To attempt theoretically to calculate the shaps of a beach profile, even for a regular train of wavee, would be sxtremely complicated since, apart from the non-uniformity of the material of the beaoh, we have to be able to oalculate the fluctuating dsgree of eaturation of the beaoh, and the effecte of drag and lift on the surfaoe particles on the beach. A point of intereat is that the peroolation of water into the beaoh will entail the flow lines of the swash flow and, to a lesser degree, the downwash flow, oonverging towards the beach and the bed velooitiee at any instant will therefore tend to be greater than they would bs over an impermeable bed of comparable roughness, where the flow linee would be parallsl to the bed. The bed profile will be expectsd generally to be convex upwards since the ratio of return to upward flow will tend to diminish higher up the beach.

Referring to Fig. 2, the force P_1 neceesary to dielodge a eubmerged pebble up a beach of gradient β and limiting angle of repose ϕ is given by

$$P_1 = mg\ (\rho s/\rho w - 1)\ \sin\ (\phi + \beta) \tag{1}$$

where ρs and ρw are reepectively epecific weight of pebble and water.

Similarly the foroe P_2 neceeeary to dielodge a pebble down the beach is given by

$$P_2 = mg\ (\rho s/\rho w - 1)\ \sin\ (\phi - \beta) \tag{2}$$

The energy flux of the swash and backwaeh may be repreeented respsctively as

$$E_1 = \tfrac{1}{2}\rho w\ V_1\ \bar{u}_1^{\,2} \tag{3}$$

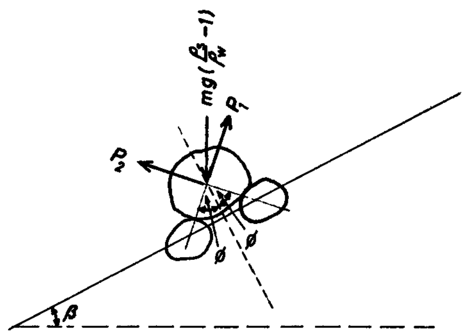


Fig 2 FORCES ACTING ON AN EXPOSED SHINGLE PEBBLE

and

$$E_2 = \tfrac{1}{2}\rho_w V_2 \bar{u}_2^{\,2} \quad (4)$$

V_1 and V_2 represent volumes of water with mean specific energy $\tfrac{1}{2}\bar{u}^2$.

P_1 may be considered as related to u, steady water velocity parallel to and up the beach, by

$$P_1 = \tfrac{1}{2}\, w\, C_c\, m\, u^2/\rho_s \quad (5)$$

where C_c is a coefficient with lift and drag components. P_2 is similarly related to velocity down the beach.

The number of uphill and downhill dislodgements may then be considered by eqns. (3), (4) and (5) to be proportional to E_1 and E_2 respectively. For a stable profile there must be a balance of dislodgements and, if $E_2 = cE_1$, from eqns. (1) and (2), considering the threshold values of P_1 and P_2,

$$c = \sin(\phi - \beta)/\sin(\phi + \beta) \quad (6)$$

i.e. $c = (\tan\phi - \tan\beta)/(\tan\phi + \tan\beta)$ (7)

a result similar to that obtained by Bagnold[1] by consideration of the work done by the swash and downwash in moving pebbles up and down the beach.

A study of natural shingle beach profiles after drawdown by storms indicates generally a profile which may be represented between beach crest and beach step level approximately as a parabola. Thus, Kemp's records[2] of three sections of the Chesil Beach (A, B and W) fit closely to the same parabola above the level of the step.

The beach grading given by Kemp[2] indicates D_{10} sizes as 6mm, 4mm and 20mm at A, B and W respectively. The coefficients of permeability are to be expected therefore to be approximately in the ratios 1.2, 1.0 and 2.2 respectively, provided the same beach grading extends to appreciable depth. One factor to explain the common profile may be the greater work done in transporting mobile beach material up and down the beach where the particle size if finer and thus compensating for lower volumetric loss (V_1-V_2) by higher specific energy loss, $(\frac{1}{2}\bar{u}_1^2 - \frac{1}{2}\bar{u}_2^2)$

A shingle beach usually exists in the presence of sand in the inshore (and often also offshore) zones. A certain amount of sand is therefore generally in suspension, following breaking of the wave, and this sand tends to percolate into the beach As a result, apart from the mobile shingle near the surface, the interstices of the beach will be more or less charged with sand, effective permeability, even of a relatively thick depth of predominant shingle, will be corresondingly reduced. The thickness of mobile shingle mainly controls the critical height and period of wave that will provoke draw-down of the beach by its incapacity to absorb an adequate fraction of the water in the swash.

There are certain typical profiles to be recognised on a shingle beach. The accreting beach has a profile concave upwards becoming convex upwards as the storm crest is reached. On the eroding beach, the concave upward curve runs into a sharp scarp at the head, with the slope immediately below the scarp standing at the critical angle of repose of the beach material. During the course of recovering, one or more secondary crests form at the limit of the swash of the breaking waves but below the upper crest, the upper crest represents the height reached by the breaking sub-critical wave at a time of high mean sea level, ('critical' wave refers to the wave that just begins to draw the beach down).

LITTORAL DRIFT OF SHINGLE

Generally rip currents play no appreciable role in longshore movement of shingle inshore of the breaker zone. This movement is caused predominantly by the direction of up-rush of the breaking wave and, though the downwash usually returns fairly directly down the beach, this contributes to a certain extent when the breaking waves approach very obliquely.

For a natural foreshore, most of the longshore movement of shingle probably occurs in the upper part of the beach. In particular, as the foreshore slope is known to vary considerably with the state of the tide during periods of storm, increased littoral drift is to be expected in an area of high tidal range, other factors remaining unchanged.

When a sea wall is present, extreme flattening of the beach occurs when storm waves come into contact with the wall, and yet higher rates of littoral drift may therefore be associated with the consequent change of profile with each tide.

With the variations of weather, tide and mobility of a shingle beach profile it is unlikely that any direct general relationship will be found between longshore energy flux and littoral drift even for the same beach, and no reliable quantitative solution of general applicability is foreseeable, without separation of the many parameters.

The concept of Pelnard-Considere[3], expressing littoral drift for given wave energy flux as directly proportional to the angle between the crest of the breaking wave and the beach line, may be expected to be applicable as a first approximation where $\sin 2\alpha \sim 2\alpha$, α being the angle of approach of the wave to the foreshore, but the interesting development of this theory by Bakker[4] cannot be applied directly to the typical shingle beach. Bakker supposes an equilibrium between variable littoral drift and the consequential onshore and offshore movement between the foreshore and the inshore area. His principle is based upon a concept of a unique stable beach profile but, as illustrated by Fig. 3, the shingle profile in the upper beach will adopt an angle so different from that of the sand in the lower beach that it is possible to have variations in size of the shingle wedge without resulting onshore and offshore motion. In consequence, where it is required to provide groynes to maintain a shingle beach, the criterion will mainly depend upon the extent to which the toe of the shingle beach extends seaward of the groyne at a time of appreciable littoral drift. It appears to be the general experience, although there are exceptions to this rule, that the sand in the inshore and offshore zones becomes adapted to the general line of the shingle beach. Thus, if the shingle can be maintained in adequate quantities to provide natural protection, the lower beach will adjust itself accordingly.

Referring to Fig. 3, if the predominant angle of approach of the wave crest to the natural coastline is α_o and the system of groynes is required to reduce littoral drift from Q_o to Q_g, then the groynes must provide a beach crest line making an angle of $\alpha_o - \alpha_g$ with the original coastline, where the suffices o and g relate to the original and the groyned conditions and α_g to the change in the angle of approach of the waves to the beach crest due to the groynes. At the present time we do not know how to relate the reduction of littoral drift $(Q_o - Q_g)$ to the extent of projection of the toe of the beach, at times of storm, beyond the seaward end of the groyne. The following makes a first attempt to such a relationship.

For a system of groynes built sufficiently high to prevent overtopping, the degree of reduction of longshore motion of shingle past each groyne will depend only on the position of the toe of the mobile beach, (probably situated at or inshore of the breaker point) relative to the end of the groyne.

If we assume that littoral drift

$$Q = K\alpha \tag{8}$$

for constant wave characteristics, where α is the angle of approach of the wave to the beach and K is a constant for the particular situation, then, where groynes cause the angle of approach of the waves to be reduced from α_o to α_g (see Fig. 3)

$$Q_o = K\alpha_o \tag{9}$$

$$Q_g = K\alpha_g \tag{10}$$

But, at a groyne, where the distance in plan of the mobile beach from crest to toe is L and the projection of the toe beyond a groyne is a, (Fig. 3), for steady flow conditions of littoral drift we may postulate

$$Q_g = K'a/L \qquad \text{where } K' = Kf(\alpha) \tag{11}$$

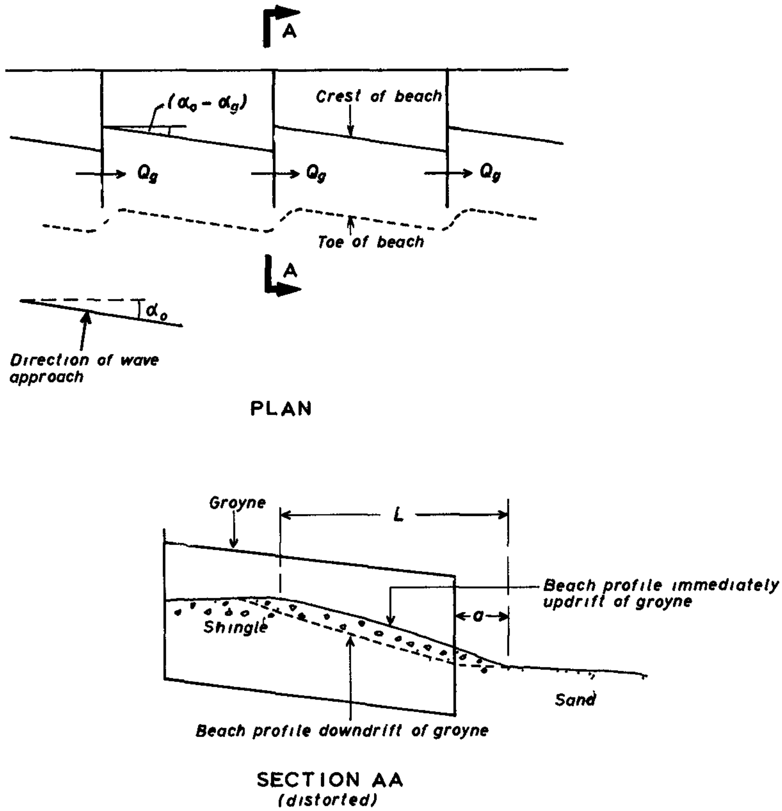


Fig 3 A SHINGLE BEACH IN EQUILIBRIUM ON A GROYNED FORESHORE

At a groyne, the line of the toe of the beach will tend to maximise drift past the groyne, i.e. locally $\alpha \rightarrow \pi/4$ if we suppose that for large values of α, $Q = \frac{K}{2} \sin 2\alpha$. Then

$$K' = K \sin \pi/4 \cos \pi/4 = K/2 \qquad (12)$$

and hence, from eqns. (10), (11) and (12),

$$Q_g \; (=K\alpha_g) = Ka/_{2L} \,. \quad \text{Hence } \alpha_g = a/_{2L}$$

whence for given values of a and L, Q_g may be estimated as a fraction of Q_o, from eqns. (9) and (10).

LONGITUDINAL SORTING OF SHINGLE

Many references may be found to the sorting of shingle by sea waves to produce longitudinal size grading along a beach. Shingle of the largest sizes tends to move towards the zone of the highest degree of exposure to the waves. A classic example of this phenomenon is found at Chesil Beach (see Fig. 1) where the most significant features are as set out in Table 1.

TABLE 1

Significant Features of Chesil Beach

Distance from West Bay (km)	Average offshore slope (0-5 fathoms)	Average longitudinal diameter of pebbles (cm)	
		Foreshore (Ref 12)	Seabed (Ref 12)
0	1:75	0.86	
6.1	1:50	1.16	4.5
7.2	1:50	1.16	3.0
11.3	1:20	1.56	2.0
12.6	1:20	1.64	3.5
15.1	1:20		3.0
17.1	1:20		4.8
21.4	1:20	3.36	3.2
23.8	1:20	3.64	5.0
25.6	1:12	4.28	6.0
28.0	1.25	5.89	

Jolliffe[6] describes a number of experiments on beaches at Deal and Winchelsea (see Fig. 1) to record the relative rate of littoral drift by means of tracer pebbles of different sizes matched to the range of pebble sizes present on the beaches. He found a significant correlation between the size of pebble and the rate of littoral drift, the size of greatest mobility being related to the wave height.

On a beach comprising an assemblage of shingle sizes, we may consider that a pebble will begin to move when drag and lift cause the pebble to rotate about a line between points of contact with other pebbles. Fig. 2 indicates how, on a beach of pebbles of different sizes, this force will bear the least ratio to the pebble mass for the pebble of the largest diameter. Moreover, once set in motion by a wave, translational and rotational inertia will tend to cause a large pebble to travel considerably further than a small one. The pebble of small size will tend to become rebedded into the beach with drag from downward percolation opposed to wave lift.

For a given beach and given wave climate there must be a size of pebble so large that it is only infrequently dislodged. Pebbles below such a size may be expected to undergo some degree of longitudinal sorting if there is a longshore component of wave energy flux. For a beach which is in long term stability, but which is subjected to different directions of littoral drift by different sizes of waves, the sorting should be a significant feature, and generally it appears so to be This effect may arise from the different degree of exposure to prevailing winds and swell or from different degrees of refraction of different types of waves.

The size grading along Chesil Beach might be explained principally by increasing exposure to the Atlantic as one proceeds along the beach towards its south-east extremity. This increase is due not only to differences in sheltering afforded by Start Point, the west headland of the bay, but also to the increasing depth of water offshore in the same sense.

Reverse drift of shingle along Chesil Beach, i.e. towards the north-west, will occur under the action of waves generated within the English Channel, but these will only be of a height to affect the smaller sizes of shingle. Further studies are warranted here to observe differences in long-shore mobility of shingle of different sizes and gradings subjected to a varying wave climate.

It is to be noted that for a beach not in long-term equilibrium little sign of longitudinal sorting is likely to be observed unless it is subjected to long-term cycles of reversal of drift. Nor is this effect likely to be observed on a groyned foreshore except in individual groyne bays, for the reason of the interference with natural drift caused by the presence of the groynes.

BEACH REPLENISHMENT: A SYSTEM OPERATED AT DUNGENESS

Possibly the finest long-term continuous records of shingle movement availabe anywhere up to the present day are those relating to Dungeness (see Fig. 1). Here the existence of a pattern of shingle ridges, looking like a magnified fingerprint, permits a reconstruction of events over nearly 2,000 years[7].

In recent years the Ness has been building out towards the east-south-east at a rate of 3-4m per year, at the expense of erosion along the south coast of the feature. As indicated in Fig. 4 the changeover from erosion to accretion occurs at a point about 700m west of the Ness proper. It will be noted that this change must be accounted for by the angle of approach becoming super-critical i.e. greater than that for maximum littoral drift, since the degree of sheltering is reduced from west to east and the extent of refraction of the dominant south-westerly waves is reduced in the same direction.

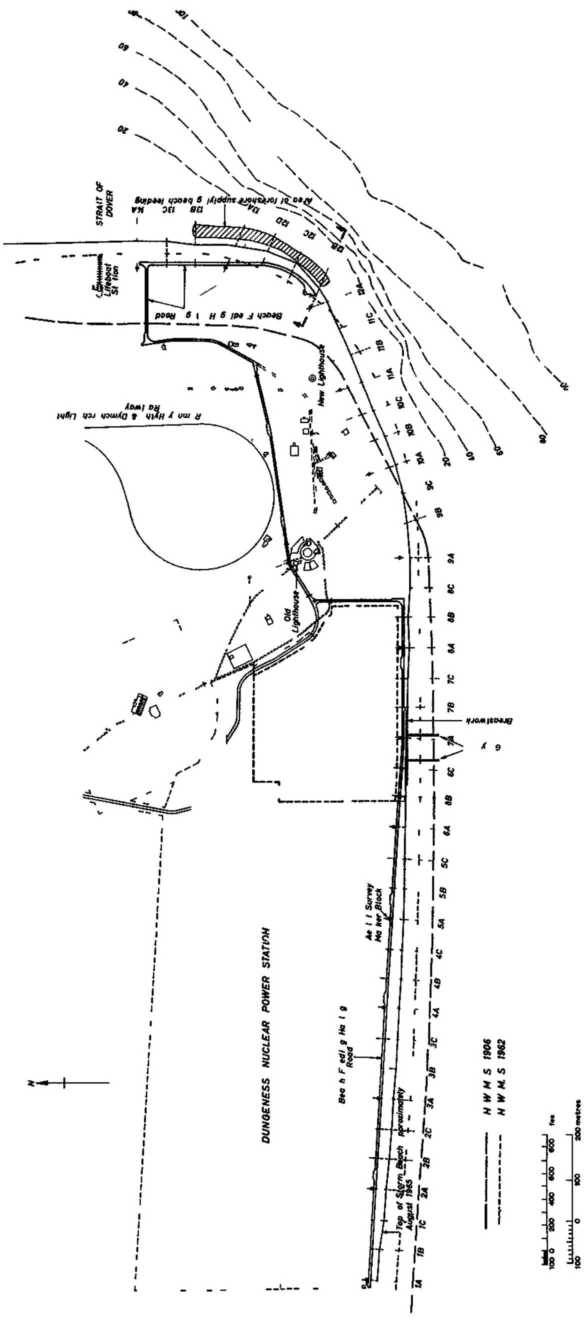


FIG 4 PLAN OF THE SOUTH-EASTERN TIP OF DUNGENESS

Since 1965 a scheme of beach recharge has been operated to stabilise the shoreline between Sections 1A and 8B (Fig. 4) where it forms a frontage to the existing and projected Nuclear Power Stations. Shingle for this purpose, won from the foreshore and upper beach in the vicinity of the Ness, has been transported each year in lorries to the Power Station frontage and tipped on the beach at recharge points. These tips build out to form shingle breakwaters on the foreshore and it is to be expected that, as they persist virtually throughout the winter, they will reduce the erosion updrift from the points of recharge.[8] Making due allowance for the local and short term variations, this effect appear to be supported by the figures set out in Table 2.

The plan of the beach has been sub-divided by section lines about 30m apart and fixed points have been selected at intervals along these lines seaward from the crest of the beach which is at about 6m above O D. (approximate mean sea level). Vertical co-ordinates of the shingle level at such points are provided each year from an aerial survey taken at the time of Low Water Spring Tides (about 3m below O D) in August. The volumes of shingle in each sub-division of the beach are then provided by a computer program and on these data the beach recharge plan for the following winter is formulated.

It is to be noted, in Table 2, that during 1965/66, the year of inception of the scheme, a considerably higher degree of beach feeding was undertaken than during subsequent years. Table 2 also indicates the annual variation in the longshore movement of shingle and in the quantity arriving at the Ness. The Power Station foreshore is now virtually stable from year to year and it seemed reasonable to assume that any variations in the beach profile below low water of spring tides could be ignored, the volume changes provided by the computer data then being actual volume changes on the beach. However, as the Ness is still advancing into deep water, allowance has now been made for the volume of shingle accretion on the steep face to the Ness below low water. The volumes of shingle arriving at the Ness, shown in Table 2, also include an allowance for accretion north of the northernmost section of the surveyed area.

In view of the detailed records available of the shingle movement over four consecutive years it was decided to study the possible relation between wave energy in the area of the Ness and the rates of erosion and accretion along the foreshore. However, there are no wave records available directly applicable to Dungeness. The nearest recorders are on the Varne and Dyck lightships, but in the enclosed waters of the eastern English Channel differential sheltering is an important factor. Consequently, since there is no significant long period swell in this part of the Channel, wind records may be used to derive at least a first order estimate of longshore wave energy flux and wind records were available from the Dungeness lighthouse. These records were analysed into durations (T) of wind speeds from points of the compass from east through south to west for winds of Beaufort Force 8 and higher.

A wave energy spectrum was then obtained, using the simplified graphical relationship prepared by Darbyshire and Draper[8] to provide maximum wave heights and thence the corresponding significant wave heights (Hs). The total annual energy flux factors ($KHs^2TC\sin 2\alpha$) were calculated and these are indicated in the final column in Table 2, the positive figures indicating energy from winds west of the south sector. The comparison of these flux factors, which are proportional to the total longshore energy flux, with the figures in Table 2 either for nett littoral drift or for material arriving at the Ness, shows no general relationship, although the highest flux factor is associated with the highest movement of material. However, the trend of recharge does generally follow the factors and with a few more years experience it might be possible to use these calculated factors to predict the quantity of recharge necessary, though some form of survey would be necessary to determine the optimal points of recharge.

TABLE 2

Shingle Recharge and Littoral Drift at Dungeness (in cubic metres)

Section of Shore		Year				
		1965-66	1966-67	1967-68	1968-69	1969-70
1A-4A	R	-	-	20600	12600	
	L	-1800	-2300	-16100	-1300	
4A-5C	R	8000	19000	-	11500	
	L	-800	-1600	-4100	-4900	
5C-7A	R	43000	-	7400	9500	
	L	-10100	1000	-700	-3400	
7A-8B	R	23000	5400	4400	6400	
	L	-900	-1000	-3000	-2200	
1A-8B	R	74000	24400	32400	40000	
	L	-13600	-3900	-23900	-11800	
Estimated quantity of shingle arriving at the Ness		80000	30000	90000	55000	
Energy flux factor		6.7	6.5	10.1	2.2	

R = Shingle Recharge
L = (Littoral drift into section) -(Littoral drift out of section)

It will be noticed in Table 2 that a large volume of recharge at a section of the shore is generally associated with a high rate of loss. This is no doubt due to the form of tipping, which is always onto the end of the tip, and where no recharge is made at the adjacent downdrift section a build up of beach only occurs against the following point of recharge. It is noticeable that in 1968-69 when a fairly even distribution of recharge was made the loss of material was also fairly evenly distributed along the beach.

Prior to 1965, the average annual loss of material along the length between Sections 1A - 8B amounted to about 25,000 cubic metres per year.

CONTROL OF A BEACH AT SEAFORD WITHOUT EXTERNAL REPLENISHMENT

The coast protection problem at Seaford (see Fig. 1) is fundamentally one of retaining a shingle beach without the benefit of natural recharge. Seaford was orignally established behind a natural shingle bank and there are many hundreds of years of history of the variations in the position of the mouth of the River Ouse through this shingle bank. Since the 18th Century the river has been trained to flow through Newhaven Harbour to the west of Seaford. From 1847 the east harbour breakwater arm has prevented easterly drift of shingle and has also affected the wave pattern that arrives around the perimeter of the bay. For the prevailing south-westerly winds this has the effect of causing a reversal of drift, i.e. towards the west, along the westernmost protected length of foreshore.

For many years sea walls and conventional groynes have been constructed at Seaford during which period the sea continued to encroach, causing considerable damage and the collapse of sea walls. The natural drift along this foreshore towards the east has not been measured but is probably of the order of 10^5cu.m of shingle per year. The economics of a beach recharge scheme have been examined but this is highly uneconomic in the absence of long term supplies of natural shingle nearby. The only alternative scheme that could continue to place reliance in natural shingle as the principal medium of protection is one that would contain the shingle along the protected length. The object was then to determine the minimum length of groyne to ensure effective containment of the shingle. An empirical approach is to suppose that a shingle beach, being relatively thin over a solid chalk bottom, may at times of storm be dragged out to sea so that its toe corresponds approximately to the breaker point of the largest waves. Model studies carried out by the Hydraulics Research Station[9] generally pointed to a similar limit of shingle movement, although allowance has to be made for the fact that, while the several relevant hydrodynamic dimensionless factors were satisfied (Yalin, 1963)[10], the material shape and grading were very different from the natural shingle.

The form of construction of long groynes decided upon had to be much more robust than conventional groynes taken out approximately to low water. The groynes, erected intially and experimentally as a timber gantry faced with steel sheet piling, were subsequently converted into mass concrete groynes built in cellular sheet-piled coffer dams. They are taken out to a point at which the bed level is approximately 6m below mean sea level (O D) and at the eastern end the principal groyne was constructed to provide, in addition, a sewer outfall.

In view of the inclination of the beach crest to the shoreline for zero drift, it is necessary to sub-divide the length into intermediate cells to avoid the need for a large amount of continuous redistribution of shingle from the east end towards the west. A small amount of redistribution can be tolerated and it is not necessary for the intermediate long groynes to be taken out far enough to achieve full cutoff. The tidal range here is approximately 3.5m on Neap Tides and 6.0m on Spring Tides. As a result, the redistribution necessary to maintain an adequate beach in the area of maximum scour (i.e. near the point of reversal of drift) amounts to about 5,000 cu.m. per year for storm waves of about 3m height and 6/7 seconds period.

Periodical aerial surveys establish that the overall shingle quantities along the foreshore remain approximately constant and also indicate the volume appropriate for periodical distribution.

An insidious cause for failure of sea walls on shingle beaches can be attributed to undermining by the sea near the time of High Water, which action can then become obscured to view on account of partial recovery of the beach a Low Water. At Seaford it was observed that, while the upper layers of shingle are maintained relatively clean as a result of the mobility of the shingle in stormy weather, the lower shingle tends to become charged with finer shingle, sand and chalk particles, carried by the water percolation through the beach. It is, consequently, possible to determine after heavy storms the depth to which the beach has been disturbed. The chalk particles act as a cementitious binder so that the side of an excavation made after a heavy storm stands vertical, immediately below the base of the mobile beach. The depth to which the beach has been disturbed at vulnerable points is recorded and compared against previous records, against the known levels of the wall footing and of the surface chalk in which, generally, at Seaford, the wall is founded. Although local availability of heavy plant for maintenance for these works facilitates this simple method of control, in the absence of such plant, some simple penetrometer device, or a heavy ring around a pile, might be used for the same purpose. At Seaford trials of alternative geophysical methods of locating the boundary were unsuccessful.

REGIME OF A NATURALLY ACCRETING BEACH

The natural regime of a shingle beach is usually confused by tides, by the presence of a well marked division between the medium to coarse shingle of the upper beach and fine to medium sand of the lower beach, also by highly variable winds and currents. The natural form of a beach may best be studied where such factors do not intervene and the characteristics of a beach in Thessalonika help to illuminate this aspect.

The beach in question is situated in a bay on the southwest coast of the Sithonia Peninsular facing the Gulf of Kassandra. The beach is contained by rock headlands and is largely composed of particles of natural quarzite graded from fine gravel to coarse sand. The schistose rocks drop away into deep water and there is little fine material in suspension in the sea. The beach material has been carried to the bay by a river which flows into it. The beach in consequence represents the stable profile of a slowly accreting beach fed from this source. Fig. 5 indicates how the grading and sorting factors vary around the margin of the bay. It is seen that the material becomes very well sorted for size as it travels away from the river mouth, with the size adjusted to the degree of exposure to the waves.

Fig. 6 shows a typical profile of the shore taken to a depth of about 30m below sea level. Contrary to the normally accepted shingle beach profile, seaward of the step, situated approximately on the breaker point for the maximum height of significant wave of about 1.7m, the shore drops steadily away into deep water, at a slope of 30°- 32° around the bay, except locally near the river mouth. The absence of an appreciable fraction below coarse sand size, coupled with a low coastal current, permits the bed material to stand at an angle a little below its natural angle of repose of about 36°. Further to seaward from this steep slope there is a variable flatter slope at a gradient of about 1 in 10 in which the material is predominantly fine sand. In Fig. 5, samples A-J are from the foreshore, samples S1, S3, S5 and S7 are from the steep inshore bed and samples S2, S4, S6 and S8 are from near the foot of the steep inshore slope.

It is interesting to compare the profile of the Sithonia beach with that at Dungeness Point (see Fig. 6) where a shingle beach is accreting in very different conditions, but nevertheless exhibits the same steep inshore feature

In general therefore one can say that a naturally accreting shingle beach will tend to develop a profile of a foreshore that is concave upwards, steepening towards the crest to the angle of repose, an onshore section flattening to a step at the breaker point, then changing seawards to a convex upward profile, finally arriving at a steep section seaward of the low water mark which assumes a slope a little flatter than the angle of repose. The lower features of this general profile, however, are frequently obscured by accumulation of sand against the shingle beach. Fine to medium sand would only accumulate at a steep angle in deep still water, on account of its susceptibility of movement by relatively small

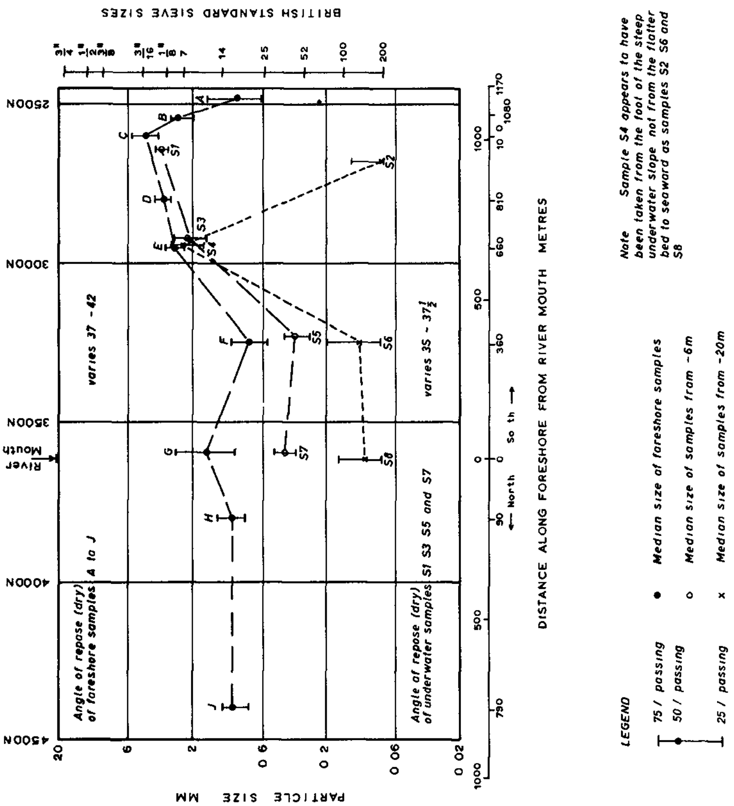
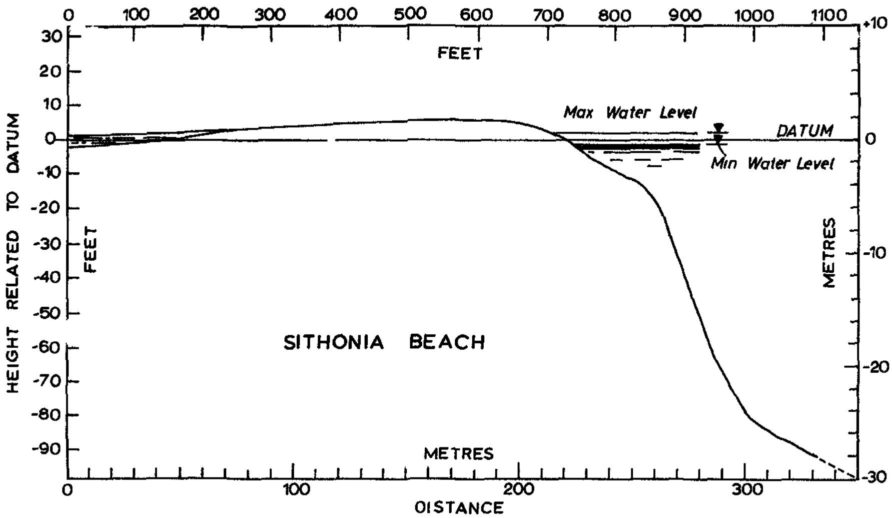


FIG 5 PARTICLE SIZE GRADING ALONG SITHONIA BEACH



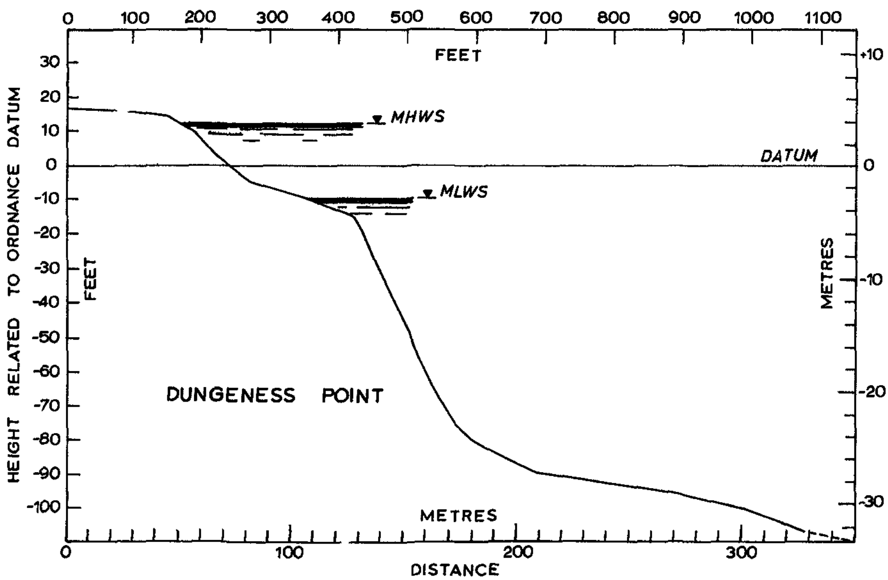


Fig 6 - PROFILE OF ACCRETING BEACHES AT SITHONIA AND DUNGENESS.

oscillatory currente, the eusceptibility being attributable not only to the grain size of the material but also to its pronenees to rippling. An eroding shingle shore, on the other hand, will not dsvelop the steep offshore feature, even in the absenoe of sand.

REFERENCES

1. Bagnold, R.A — Mechanics of marine ssdimentation, The Sea, 3, Intersciesnce Bublishere Inc., (1963) pp 507-528

2. Kemp, P H — A field study of wavs action on natural beachss, I A H.R. Xth Congress, 1, Paper 1.18 (1963) pp 131-138

3. Pelnard-Considers R. — Eseai de theorie de l'evolution dss formes de rivage en plage de eable et de galets IV isme Journéee de L'Hydraulique Question IV (Paris) 1956.

4. Bakker, W T — The dynamics of a coast with a groyne syetem. XIth Conf. on Coastal Enginsering, London (1968) Vol II pp 492-517

5. Carr, A.P. — Size grading along a pebble beach Chesil Bsach, England Jnl. of Sedimentary Petrology, Vol 39, No 1 (Mar 69) pp 297-311

6 Jolliffe, I P — Experiments designed to compars the relative rates of movement of different sizes of beach pebble. Proc. Geol. Assoc. Vol 75 (1964) pp 67-86.

7. Lewis, W.V. — The formation of Dungenees Foreland. Geogr. Jnl. Vol 60 (1932) pp 309-324.

8. Derbyshirs, M. & Drapsr, L. — Forecasting wind-generated ssa waves, Enginsering (5th April 1963) pp 482-484.

9. Hydraulics Ressarch Station — Seaford Sea Wall: protection by artificial fill. Report EX 209 (May 1963).

10. Yalin, M.S — A model shingle beach with permeability and drag forces reproduced. XIth Congress Int. Assoc. Hyd. Rss., London (1963).

11. Nsate, D J M — Underwater pebble grading of Cheeil Beach. Proc. Geol. Assoc. Vol 78 (1967) Pr. 3 pp 419-426.

Note Tabls 2 reproduced by permission of South Eastern Region of the Central Electricity Generating Board