PALM BEACH

PART 2

COASTAL SEDIMENT PROBLEMS

PALM BEACH

CHAPTER 17

THE ORIGIN AND STABILITY OF BEACHES

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THE ORIGIN OF BEACHES

One should not lose sight of the fact that the origin of beaches goes back into antiquity. The story begins with the origin of matter and continues through the aeons with the evolution of the solar system and the appearance of the Earth as a fiery ball gyrating in space. As one's focus narrows there is to be seen the cooling of that ball, the formation of dense clouds of water vapour in the atmosphere, the torrential rains and the beginnings of the seas. Perhaps it is at this point that the introduction is completed and the real story of the beaches begins, for with the rains came erosion of the land masses, and the transportation of the eroded material by river and rivulet towards the sea. At the brink of the ocean a brief halt is called in its journey, for here a portion of this eroded material takes position as beaches around the coast, before ultimately joining the remainder in the depths of the sea. For many thousands of years the sediment so formed and transported collected on the sea bed, consolidated and hardened and was transformed into the sedimentary rocks which, by adjustments in the Earth's crust, were later lifted above the surface of the sea to form new islands and continents. Still the rains fall, although perhaps not so heavily as before; still the processes of erosion continue upon the land masses, old and new; still a part of the products of this erosion remain for a while at the coastal fringe before they pass on to the ocean depths - the raw material of what may be, by completion of the cycle, the continents of tomorrow. Such is the sequence of events over a period of millions of years and, as the process continues during the millions of years which the future holds, the existing land masses will no doubt be eroded away and the materials of which they are composed will finally rest again on the bed of the sea. For so long as the seas have washed the shores, and the rains have fallen and reduced the mountains and high places, there have been beaches. Those beaches which are found today may have existed from time immemorial in some form or other, perhaps since before life appeared on the surface of the Earth. Due to their position in the pattern of Nature they will have changed as the coastline changed, and as the eroded ingredients of the land which formed them changed. They will have grown when the new material supply exceeded the wastage, and they will have diminished when the wastage was more rapid than the replenishment. The changes which are taking place today and which are engaging the attention of the Civil Engineer, form an infinitesimally small incident in the history of the beaches; and in the considerations of the Engineer they should be related to the whole, of which they form a part.

Quantitative Equilibrium of Beach Material.

Eroded material, from whatever source, passes inevitably into the depths of the sea in the form of silt. It is a journey of no return, for there it will remain until resurrected by some immense adjustment of the Earth's crust capable of raising the sea bed above the surface of the waters. There is no natural process which conveys these sedimentary deposits back along a return route to cast them up around the coasts, and the origin of beaches must be sought, not in the basin of the sea, but in the land masses from which they are truly derived. The accumulations of sand and shingle which exist as beache around the perimeters of the land masses, represent a transitional stage in the conveyance of eroded material from the land to the sea. They are the coarser materials which have been rejected by the sea and imprisoned on the beaches to be submitted once more to the mills of Nature and ground down to a degree of fineness acceptable to the discriminating sea. By the constant application of the waves the coarser materials of the beach are ground against each other, gradual wearing each other away to the fine silt which as it is formed is take up into suspension in the sea water, conveyed out to sea and deposited upon the ocean bed. As previously remarked, when the material which is added to the beach from new destruction of the land exceeds the wastage, the beach will grow in size, but, when the supply is diminished or cut off and cannot therefore make good wastage, the beach becomes smaller and suffers erosion. Thus a balance, or equilibrium is maintained by Nature, for a large well-formed beach protects in some measure the lands to be found in the rear, such that the rate of destruction is thereby slowed down. Were the beach to be diminished in size the waves would more readily have access to the cliffs which would be attacked and broken down to form new beach material. In this way Nature seeks not to destroy indiscriminately but rather to preserve, for, by affording this protective screen of beaches around the softer parts of the coast, the rate of erosion of the land is reduced to a minimum and only such material is taken as is essentially required to maintain the bulk of the beach. It might be appropriate to consider at this point what would have been the effect upon the land masses had the Laws of Nature been so arranged that material eroded from the cliffs was forthwith swept away and dissipated by the sea. In this eventuality the waves would, with every tide, have access to the land and would exact a contribution from the 'soft' cliffs. It is considered not unlikely that, in the long interval of time which has elapsed, many of the softer coastal districts would have eroded away; and the map of the world would be very different from what it is now. In this way, by gracious natural laws, Nature has preserved our country from erosion by the sea; and the inevitabl minimum of destruction which is receiving popular attention today might well be reviewed against the gigantic erosive activity which, i the absence of protective beaches, could have taken place along the coasts.

Segregation - Critical Size.

The sea segregates the eroded matter with which it has to deal in many ways. Thus there is a difference between material which may be transported into the depths of the sea and material which must remain imprisoned on the beaches. In order that a particle may pass below low water mark it must be sufficiently fine for it to be taken up into suspension, and to remain so for an adequate length of time for it to be conveyed into deeper water and there deposited on the sea bed. Particles which are greater than this Critical Size remain above low water as sand or shingle beaches, confined by forces which will be described later. Even that material which is admitted to the sea bed is assorted, so that the finest is to be found at the greatest distance from the shore. In order to establish what that Critical Size of particle might be, the Authors carried out a number of investigations into the nature of the deposits on the sea bed below low water mark at a depth below which the average wave might be presumed to have little effect, namely about one fathom. A number of pebble beaches were tested in the Torbay area and were found to change at this depth to a fine silt but it was the sand beaches which received particular attention because the information required was the size of particle above which all particles remained on the beach and below which they were taken into suspension and conveyed to the sea bed. A number of samples were obtained which were then dried and analysed by passing through British Standard Sieves. It was established that the Critical Size was that corresponding approximately to a sieve of 100 meshes to the inch, for nearly all the silt obtained from below low water mark passed through the sieve, whilst the sand above low water mark was largely retained upon it. It was in fact remarkable how little fine material was retained on the beach and how little coarse sand had found its way below sea level. The Critical Size may vary in different localities. The importance of this investigation is in its influence on one's attitude to the sea bed as a potential source of beach material. It had once been considered by the Authors that a possible way of building up a beach would be to e xcavate material from the sea bed by means of a dredger or similar machine; then to place it upon the beach where it could be stabilised by a system of groynes. In view of the nature of the bed material, however, it is clear that such a proposal would be impracticable for, after a while, the fine silt would be taken up again into suspension and returned to the bed of the sea. All material placed upon a beach to build it up should, therefore, be of a size coarser than the Critical Size described above. The experiment also points to the unlikelihood of beaches having their origin in the bed of the sea.

Sources of Origin of Beach Material.

Beaches are formed from the destruction of the coast by the waves and from the eroded matter brought down to the coast by rivers. The former are usually pebble beaches and the latter sand, although sometimes cliffs break down into sand instead of pebbles. Sometimes

both sources contribute towards the material of a beach. The best beaches are those produced by the destruction of the 'soft' coastline for the gravel and sand is ideal material and has been available until recently in unlimited supplies. Many miles of this 'soft' easily eroded foreshore have recently been protected from further destruction by the construction of sea walls and is no longer available as a source of raw material for the beaches. It is feared that, as a result, those dependent beaches will soon become depleted and will ultimately vanish, and, accordingly, it becomes the duty of the Engineer to conserve what remains to the best advantage. No doubt factors which affect the discharge of rivers, such as impounding dams, reservoirs and drainage systems, will influenoe the supply of material to the beaches and may to some extent be responsible for 'erosion'. The foregoing remarks have dealt with some aspects of the origin of beaches in general terms, and it is hoped that they may be applied with profit to particular cases. It is now intended to deal with matters relating to the distribution of the material once it is located on the beach, for, sometimes, it is found to be occupying a situation distant from its point of deposition on the foreshore. Thus knowledge of the processes involved would be an advantage.

Waves.

Waves are essentially surface phenomena. As they move they impart to the water what has been desoribed as a rotary movement, the direction of rotation being forward near the surfaoe and in the reverse direction at depth. This agitation diminishes with increasing depth below the surface and, because as might be expected the larger waves are more violent in their action and have a greater field of influence, the degree is related to the size of the wave. As the effect decrease with depth, there eventually becomes a position where it may be disregarded and, subject to the discretion of the Engineer, this may be taken as one and a half times the wave height. Thus below this depth the effect of the wave upon the sea bed becomes negligible and consists only of such slight movement as would disturb the finer silts. When a wave breaks upon a beach, its character changes. The potential ener with which it is charged, and the ordered rotation of particles of water which represents its kinetic energy are lost, and the wave become simply a body of water moving directly upon the slope of the beach. With impact, a further transformation of its energy occurs. Some is absorbed by the material of the beach as it is conveyed up the slope an is ground particle against particle; some is dissipated as eddies as the violence of the impact produces the familiar froth and foam; some is absorbed by friction as the water penetrates the permeable mass of the beach; and some is transformed into potential energy as the water flows up the beach as 'swash' before eventually halting and returning to the body of the sea. As this potential energy is again converted into kinetic energy in the flow of water seawards, it is again able to pick up and transport beach material down the slope of the beach until it is met by the next oncoming wave when the cycle is repeated over again.

It would appear that at the particular slope of the beach which will be described as the 'Slope of Equilibrium', the amount of material moved up the beach by the advancing wave is balanced by the amount which is drawn down by the receding water. Were the slope at any time to be too steep, then more would be drawn down than cast up, and vice versa. Thus Nature automatically adjusts the slope of the beach. It will be clear that, the beach being arranged on the slope, the force of gravity impedes the passage of material up the beach, whilst assisting its downward journey. Thus the excessive energy of the advancing wave compared with diminished resources of the receding water is compensated in its effect by the bias introduced by the force of gravity. The energy of the advancing wave which is expended upon the beach must, of necessity, be greater than that amount which is returned to the sea by the receding water. Therefore it follows that the overall effect of the waves is to impart energy to the beach and to exert a force upon the aggregation of the beach particles; this force acts towards the shore in the direction of travel of the waves. Thus, if the average force of the waves is towards the land, there cannot be an overall movement of beach material seaward in opposition to this force. Beach material is imprisoned upon the beach and any mass movement of this material must be confined within the approximate limits of high and low water. Consider the application of this principle, namely, that the action of the waves is such that the material of a beach (provided it is coarser than a particular critical value at which it might be taken up into suspension) is compelled to remain approximately above the level of low water mark. There will be seen here justification for the claim that a physical obstruction such as an impermeable groyne or a headland across a beach would effectively prevent the passage of material in a longitudinal direction. In a similar manner, the channel of a river intersecting a foreshore, if it were deeper than about a fathom at low tide, would be equally effective in opposing the passage of material, for the action of the waves would prevent the beach material from gaining access to the bed of the river and crossing to the other side. This phenomenon is illustrated at Westward Ho, on the North Devon coast, where the River Torridge discharges into the Atlantic. Those familiar with the area will recall that the river channel almost bisects the unit of beach between Saunton Cliffs at the north-east and Hartland Cliff at the west. The famous pebble ridge was formed from the destruction of the latter cliffs coupled with the gradual distribution of the eroded material along the foreshore, until it extended along the estuary of the river, resting on the alluvial clays. It will be observed that the eastward drift has aocumulated a vast bank of pebbles south of the river, but it will also be observed that none of these have succeeded in crossing the river to Saunton Sands.

Summary of Principles.

There may be those who would say that this subject matter does not warrant the choioe of title in so far as the Paper has not dealt individually in detail with specific cases. Such was not the intention; rather was it the object to discuss certain general principles bearing

on the subject which the Engineer must take into account when he is investigating the origin of a particular beach. Those principles are now set out in concise form as under.

1. Beach material does not originate in the sea.

2. Beaches originate firstly in the destruction of the coast and secondly from material brought down to the coast by rivers.

3. Movement of beach material is confined within the approximate limits of low and high water.

4. Longitudinal movement of beach material may be completely intercepted by barriers across the beach which may be headlands, impermeable groynes or rivers.

5. A unit of beach between any pair of barriers is independent and isolated from the adjacent foreshore.

6. In order that material may remain in position on the beach, the particles must be greater than the Critical Size (100-mesh sieve approximately). Material less than this will be taken into suspension and conveyed out to sea.

These remarks would not be complete without reference to certain views which have influenced opinion and exerted something of a strangle hold on the course of coast protection measures in the past. This Paper is based upon fundamental facts, namely, that beach material of a kind similar to that found on the beaches is not generally to be found on the sea bed, and also that natural forces do not exist which could convey material along the upward slope of the sea bed in the direction of the shore to deposit it ultimately upon the beach. It has been suggested that there are cases where some beach material is of a character dissimilar to that of the adjacent coast or countryside, and it is contended on this account that, because the beaches do not consist of material geologically similar to the cliffs or river deposit in the vicinity, then it necessarily follows that it must have come from the bed of the sea. This argument is negative in character and is submitted only in default of other explanations for the accident of these strange ingredients. For complete proof, evidence should be produced showing that such material may be found on the bed of the sea and that the necessary transportation on to the beach could be effected under natural conditions. The origins of beaches are in some cases simple to establish, in others difficult, and perhaps nobody will ever tell their full story. The reader should return to the opening sentence of this Paper and consider how the origin of a beach may be lost in the mists of geological time; for who can penetrate the tens or hundreds of thousands of years and follow the adventures of a flint now resting on a south coast beach, which was formed in the great chalk bed which once existed.

THE FOUNDATION OF BEACHES

The wave is the cutting edge of the sea. Year by year the coastal perimeters of the land masses are subjected to the destructive onslaught of the sea, and with the wave as its tool the solid rocks are reduced to sediment. Over a period of infinite time enormous areas of coastal

lands have thus been destroyed and have left as evidence the "Continental Shelf" which is a wave cut platform marking the advance of the sea since the continents were first formed. All the erosive qualities of Nature seem to be embodied in the wave. It has corrosive properties which soften the rock, it is capable of developing immense hydraulic pressures whereby the rock may be shattered, and by taking up the fragments into its moving stream, continual abrasive actioh may be exerted upon the rock face within the limits of wave activity, i.e. in the vertical band between high and low water mark. Eventually when the cliff above these levels is undermined and can no longer sustain itself, it collapses and in time forms the aggregate of which many beaches are composed. The foundation of a beach was therefore the wave cut platform upon which the debris of destruction had been deposited. According to the geological structure of the coastline, so the foundation of the beach varied. When the coastline was hard in character, consisting of granite, limestone, sandstone, chalk etc. there was a distinct plane of demarcation between the foundation and the beach itself. This was not so evident when the coastline was soft, consisting of sand or gravel for then the beach material was very similar in character to the foundation and only careful scrutiny would reveal the difference. There were also cases where beaches consisted of material which had drifted along the coast and formed along the perimeter of low lying land, in which cases the foundation of the beach might be a clay strata. In all cases however, a beach must have a solid foundation, the surface level of which must lie above or close to low water mark. The movement of beach material by the waves was confined within the approximate limits of high and low water and beach material could not usually be conveyed to, or deposited upon a foundation situated below this level. The nature and position of the foundation of a beach intimately concerned the Engineer, for it was upon this that he supported his works in order to give them strength and stability. The value of preliminary trial boreholes thus became evident and designs for constructional works should preferably be preceded by an investigation into the foundation of the beach.

Slope of Equilibrium.

Upon the foundation so formed, the aggregate of the beach, whether it be sand or pebbles, is deposited, and is so assorted by the waves as to take up a specific configuration in which a state of equilibrium is established. During the changes which take place to suit the vagaries of the weather, the surface of the beach may be affected by numerous incidental phenomena such as berms or channels, but it is desirable to look beyond these casual corrugations to seek the important truths which lie beneath. It may be established by inspection that the surface of the beach in contact with the waves within the limits of high and low water mark takes upon itself a uniform slope. This might be expected from academic considerations for during the interval of a tide when wave conditions might be expected to be constant, it would be unreasonable to expect different slopes at different levels, with comparable material. It may be further established by observation that materials of a similar degree of coarseness adopt a similar angle of inclination to the

horizontal wherevever they may be found along the coast; again if the external conditions are comparable. Finally it may be observed that the angle of inclination at which the beach is maintained between high and low water marks is related to the coarseness of the beach material, being steeper where the material is large, and flatter when it is fine. When the beach material has established itself in equilibrium with respect to the waves, this angle has been termed the "Slope of Equilibrium". Appropriate values of the Slope are as follows:- Fine Sand 1 in 50; Coarse Sand 1 in 20; Small Pebbles 1 in 10; Large Pebbles 1 in 4. These values are intended as a guide and the Engineer should take measurements on the site before committing himself to the design of sea defence works. The "Slope of Equilibrium" may be susceptible in some degree to numerous extraneous factors such as the density or porosity of the material, and the special forms of wave which might encounter the beach, but these variations are not of great practical significance. It is certainly affected to a marked degree by any feature which creates excessive turbulence in the ordered breaking of the wave, such as a vertical sea wall, rocks or similar obstructions. The passage of large quantities of subsoil water through or over the beach also reduces the angle of slope. There are many instances of beaches which consist of two different materials, sand and pebbles which are segregated from each other such that the fine material occupies the lower situation and the corase is thrust to the head of the beach. In such cases each class of material takes up its appropriate Slope of Equilibrium. Similarly when one end of a beach consists of material finer in character than the other, again each material takes up its appropriate slope.

THE STABILITY OF BEACHES

The force and the power of the sea is acknowledged by all. Its effect upon man's constructive efforts is to be found in the heaps of broken masonry which may be discovered around the shores after a storm Why is it, therefore, that whilst structures are frequently destroyed, the accumulation of loose particles of material, pebbles and sand, comprising protective beaches around the coast, are able to withstand the onslaught of wind and tide? There is no resistance inherent in the individual particle. It is readily moved by the smallest wave and yet in the aggregate, these insignificant entities are able to prove a bulwark to the sea. It is the state of equilibrium which is established within such banks by the inter-action of one particle upon another related to the forces of the waves which gives them the strength to resist the violence of the sea. It is not true, however, that all beaches are capable of equally resisting the power of the sea. Some of them are afflicted by the disease of wastage imposed by either natural or artificial causes. Some sections of the coast, however, are fortunate in being relatively free from erosion, and happily their natural beauty remains unspoilt by those devices which have been found necessary to protect other parts from the ravages of the sea. Having become familiar with the varying scene presented by the coastline, the observer will become conscious of certain

features or characteristics of the stable stretches, which do not appear in those which are subjected to severe wastage. He will first realise the ordered nature of the stable beach, contrasted with the irregularities and disorderliness of the unstable beach. He will note the wonderful sweep of the Chesil Bank, for instance, as his eye reaches for its farthest end, eighteen miles away, and he will realise that he is viewing a manifestation of controlling natural laws. He will then note the presence of headlands or barriers at each end which would appear to support and contain the material within prescribed limits. This phenomenon can be interpreted as a necessary condition for a stable beach; such that the absence of one or both of these barriers would automatically render the beach unstable. The most signifioant feature of a stable beach of the type described is the curvature. The waves and tides of perhaps thousands of years will have shaped the beach into a regular curve from end to end until a state of equilibrium has been established, in which configuration it will remain unless, due to changed circumstances, it is disturbed. It is a necessary condition of stability in such a beach that it should be capable of assuming, between its limiting barriers, such a curve. The nature of this curve of equilibrium has received special attention from the Authors.

Barriers - Groynes.

Consider first the nature and functions of the barriers which support the extremities of a stable beach. They appear naturally as headlands and artificially as groynes and jetties, provided that the latter are impermeable and do not transmit beach material through them; are substantial in construction such that they may withstand the thrust imposed upon them; and in size are able to contain the full cross-section of the beach for such distance below low water mark as satisfactorily to prevent beach material from passing around this extremity. If there exists such a barrier at each extremity of a length of beach, then the first essential condition for stability will have been complied with. For a great many years efforts have been made to combat erosion by the construction of artificial devices such as those described. In many parts of the world erosion manifests itself in a drift of beach material along the coast, and no doubt in the early days it was instinctively felt that an obstruction to such passage would have a beneficial effect. Thus timber barriers or groynes were no doubt first constructed to prevent such movement. With the passing of time, however, the custom has grown to apply groynes wherever erosion is taking place without reference to their precise functions which, in any case, have seemed very obscure. In many instances it is clear that to them have been attributed magical properties whereby they might conjure beach material out of the sea into their outstretched arms. Such a conception is, of course, nonsense, as a groyne can only control beach material which already exists in position on the foreshore. The civil engineer, in the course of his varied duties, will have become acquainted with the properties of sand. He will have encountered it dry, under which condition it is held to provide a good foundation, and he will have encountered it

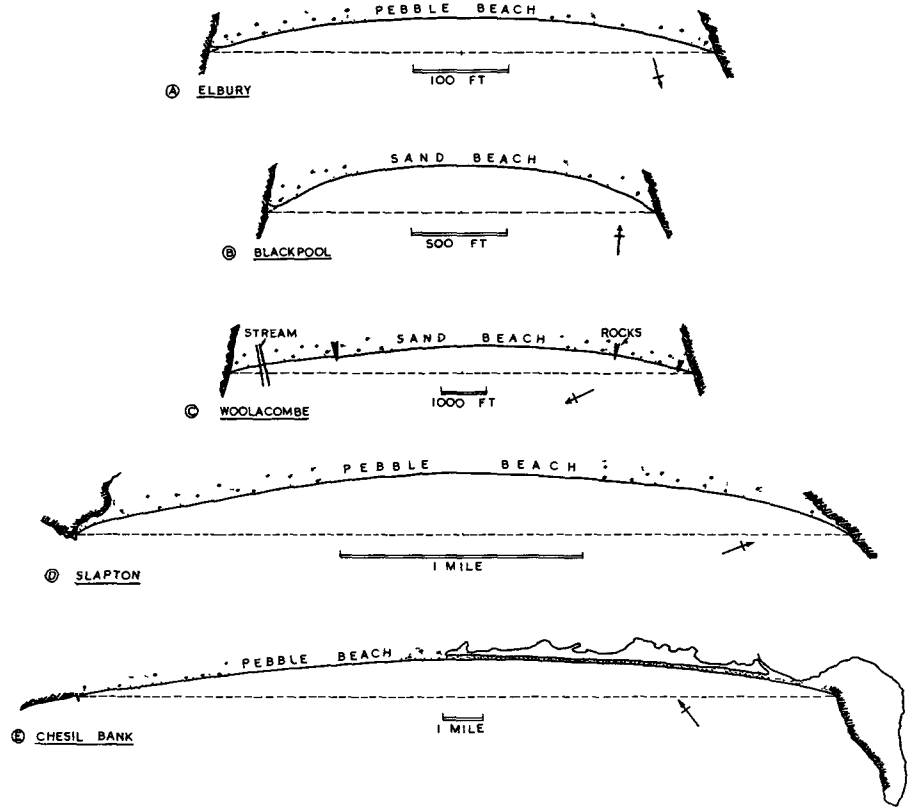

Fig. 1. The shapes in plan of a selection of beaches which are considered stable. They are between 525 feet and 18 miles long; some are pebble and some sand beaches. Note the arc formation.

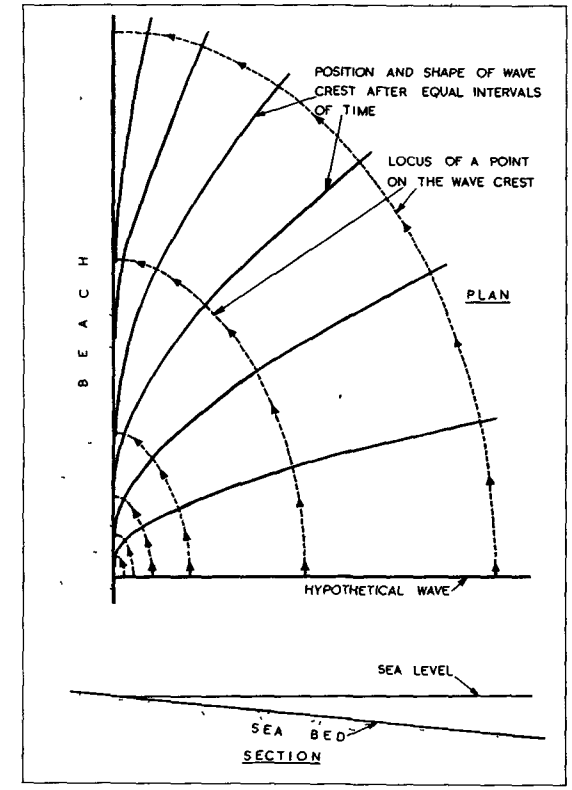

Fig. 2. Diagram showing how a hypothetical wave crest moving across the contours of the sea bed is thereby distorted. As computed from the formula $c^2 = gh$

wet as running sand which has no substance and behaves as a liquid. In the latter case it presents a major engineering problem, and it will be remembered that it is often necessary to contain it within sheet piling in order to give it the capacity to withstand load. Thus, by the application of compression to its bulk, running sand may be stabilised. The same material is found on the beaches under similar conditions. Water-logged sand below the level of the water may appear hard and firm to the foot, but a handful runs between the fingers like water, and the cavity in the beach from which it has been taken is quickly filled by other material which flows in from all sides. In the first case the sand is compressed; in the second the pressure has been released and the stability has been lost. It is an essential condition of stability in a beach that the particles of which it is composed shall be in a state of compression, and it is this compression transmitted from particle to particle throughout the length of the beach, which finally thrusts upon and is resisted by the barriers at each end. Thus the first function of a groyne must be that of a retaining wall capable of withstanding the longitudinal thrust of the beach. Moreover, although the above remarks refer to sand, the principle is equally true when the medium is coarser in character. In order that a groyne may fulfil its purpose properly, it must be impermeable to the passage of beach material and must be large enough to embrace the cross-sectional area of the beach which it is intended to stabilise. The beach must be supported beyond the highest tide and below the lowest low water, unless special circumstances apply. Of course, account will be taken of practical difficulties of construction when these rules are interpreted. Thus, by virtue of the explanation just given, it will be seen that the groyne has subtly changed in character from the mere obstruction to the passage of material to a precise instrument for imparting to the beach material an essential element of stability, i.e., compression. It will be appreciated also that the beach material can no longer be considered as able to move across the groyne barriers in its drift for, once trapped and stabilised between any pair of properly designed groynes, it is permanently established there.

Arc of Equilibrium.

The Authors investigated the nature and properties of that 'curve of equilibrium' of a beach which might properly be associated with stability. A number of beaches which fell into the stable category were considered and a selection was made of those which provided the greatest variety both in length and in class of material. In all cases these beaches were supported by a barrier at each end, and were comparatively free from external influences such as groynes and sea walls which were known to have an independent effect. With the aid of ordnance survey maps and by taking measurements on the site, the appropriate 'curves of equilibrium' were established and recorded together with other relevant information, (Fig. 1.) A close examination reveals that, when allowance has been made for local influences for which an explanation is afforded, the curve approximates to an arc

of a circle. At the ends a slight deviation is sometimes exhibited which is no doubt the result of the influence which the barriers themselves exert upon the beach, and irregularities due to special physical conditions such as streams or rocks are evident. It is sufficient at this stage to indicate that the variation from a true circular arc is due to local conditions, and that in a 'perfect case' the curve of equilibrium would be an arc of a circle, which in future will be referred to as the 'Arc of Equilibrium'.

Rule of Similar Arcs.

It was further decided to examine the nature of the angle subtended at the centre of the circle by the arc of equilibrium, and it was established that these angles are nearly the same in each case, which is a remarkable fact when considered in relation to the enormous disparity in length and character of the beaches examined. The Authors crystallised this property as the 'Rule of Similar Arcs', whereby it is to be understood that 'Provided that such beaches, including the portion which extends for a material distance beneath th sea, consist of particles capable of being moved individually by the s then the "arcs of equilibrium" of all these beaches will be geometrically similar arcs, each subtending an angle of approximately 0.25 radians at the centre of its circle!. The nature of the undersea bed affects the curve of equilibrium; thus it was necessary to introduce the proviso. This principle, nevertheless, has an important and usefu application in practice.

Conditions of Beach Stability.

Before going on to examine the application of the principles expounded to practical problems of sea defence, it would be as well to assemble them in a concise form as under. It is submitted that essential conditions of stability in a beach of this class are:-

1. The beach shall be supported at each end.
2. Between the end supports the beach shall have assumed a curved shape, termed the arc of equilibrium, and the angle subtended a the centre of the arc shall be approximately 0.25 radians.
3. The slope of the beach shall have taken up its appropriate slope of equilibrium.
4. The orientation of the beach shall have been established cor sistent with prevailing climatic conditions. This will be discussed later.

The Application of Groynes to Foreshore Stabilisation.

An attempt will now be made to present the behaviour of beach material in association with the waves, as a picture of the ordered application of the foregoing principles. Let us suppose that upon a length of foreshore are tipped several million tons of beach material which are placed indiscriminately in contact with the sea. Consider what will happen to it in association with the waves. The accumulati

of material will not, of course, be in stable form in accordance with the requirements just set down, and the loosely arranged material will begin to be moved freely at the dictates of wind and wave. First, throughout the length of the beach, the slope of equilibrium will be established; wherever the slope is too steep material would be dragged down; wherever it is too flat it would be filled in; so that ultimately an even slope would be established appropriate to the material used. Gradually, under the action of the waves, the material would then be extended along the foreshore until brought to a halt by a 'barrier' at each end. Finally, it would be shaped and moulded until the arc of equilibrium had been established. This activity is going on at all times around the coast; the waves are ceaselessly moving and shaping the beach material in an effort to reproduce the configuration for stability. What happens when the shape of the coastline is such that the requirements of stability cannot be met? There are examples where the barriers are miles apart and the coastline between is of such a character and such a shape that it is a physical impossibility for the curve of equilibrium to be imposed upon it. Under such conditions stability cannot be established and the loose material will be moved by the waves, sometimes to the left, sometimes to the right, in endless search for a final resting place. It would be an exceptional case, however, if the cumulative movement to the right exactly equalled that to the left; the accident of weather would introduce a bias in one direction which would reveal itself in a general movement of material longitudinally along the foreshore - hence drift. The engineer is frequently confronted with the problem of how to deal with this situation and to prevent drift of beach material from parts of the foreshore where it is required, to places where it is not. He has usually met the problem by following past example and constructing groynes across the foreshore but the results have not always been successful and have in some cases been harmful. The use of groynes in such a case is, in fact, the correct solution to the problem, provided they are scientifically designed, their object being to divide a long and unstable section of foreshore into shorter sections such that the conditions of stability can be physically applied to each separate section. Each of these sub-divisions would, in fact, constitute a separate stable beach. It will be seen that considerable control can be exercised over the beach material of a foreshore by arranging the spacing of the groynes to suit requirements. In fact, beaches can be 'designed', and the resulting configuration of the beach produced, can be anticipated in advance and designated on a plan. In other words, the effect of the groynes can be predicted and measured.

Unstable Beaches.

Natural processes operating along the foreshores are such that there is a tendency for loose material to drift and for erosion of the coast to be ordered, so that eventually a stable configuration is established. One would have thought that after many thousands of years these continued adjustments would have produced a universally stable coast in appropriate configuration. Why is it then that some

sections of coastline do not conform and are subject to increased beach displacements and more severe erosion? Consider, for example, a stretch of 'soft' coastline many miles in length such as might be encountered in Norfolk and Suffolk, and let us imagine that it is entirely stable, made up of cliff barriers, bays (arcs of equilibrium), etc. Displacements of beach material and the overall rate of erosion will have been reduced to the minimum. This satisfactory state of affairs, however, is affected by other processes which lead to the destruction of the equilibrium. Most susceptible to the violence of the sea are the exposed headlands. They probably represent the more tenacious portions of the coast, but even these, when they consist of sand, gravels, and clays of varying consistency, have sometimes to succomb rapidly to the waves. There are times in the history of the coastline when those headlands under the impact of the sea are so reduced in size that they are no longer able to fulfil their functions as barriers. Thus the equilibrium of the coastline is disturbed, units of beach become merged with one another and the line of the foreshore becomes confused. This irregular line reflects the transitional stage which has been established and denotes that the shaping forces of the patient sea are once more at work in remoulding the coastline towards a new equilibrium configuration, with increased local erosion as a result. The significance and the importance of the headland in the structure of the coast will be clear. The whole line of the coast depends upon these salient features and the general rate of erosion is determined by the particular rate at these controlling points. When, therefore, schemes are being considered which are directed towards the protection of long lengths of 'soft' coastline, the attentic of the engineer should first be attracted towards these features, and their preservation should become a prior need.

THE ORIENTATION OF BEACHES

Those who reside by the sea will be familiar with the changing aspect of the coast as it appears in fair weather and foul, sometimes with the surface of the sea lashed to a fury by gales, with great breakers charging up the beach, and at other times like a placid lake with gentle waves idly spilling themselves on the sand and shingle. Throughout the variety of changing circumstances and different complexions of the marine panorama one thing, however, in particular remains unchanged, namely that waves travel from the horizon towards the land, never in the opposite direction. The close observer will note, in fact, that on a calm day the waves at the point of breaking on the beach will be arranged with their crests almost parallel with the shore line and that only under the influence of a severe cross wind will they be slightly deflected out of this configuration. So marked is this phenomenon that the Authors have observed along the famous Chesil Bank, Dorset, long rollers coming inwards from the Channe making almost instantaneous contact with the beach over a stretch many miles in length. What is the explanation of this phenomenon, and what natural laws are invoked to produce this manifestation of nature's controlling hand?

THE ORIGIN AND STABILITY OF BEACHES

Conditions for Stability of Beaches.

An attempt has been made to analyse and establish those natural laws which are related to the stability of beaches. The first of those laws to be described concerns the slope at which the beach material could sustain itself in association with the sea, and to this property was given the particular name 'Slope of Equilibrium' because it was conceived that at this inclination the beach would have established itself in a state of equilibrium. It was also shown that for a beach to be in a state of equilibrium it was necessary for it to be contained or supported at each end in order that a compressive thrust might be exerted throughout its length. Finally, it was also shown that between the two end supports the surface plane of the beach would have to assume such configuration that all contours between high- and low-water mark would be arcs of circles, which were designated 'Arcs of Equilibrium'. It would be appropriate at this point to indicate what is meant by the terms stability and equilibrium. When this investigation first commenced, it was with the belief that there were two basic classes of beach, those which were stable and those which were not. The latter were naturally receiving a great deal of attention at the expense of the former, and the mass displacement of beach material, usually due to drift, was causing some concern in many localities. It was thought that an investigation into the characteristics of the two classes might reveal why one should be stable and the other not. Thus, at first, stability referred in broad general terms to the nature of the beach and its freedom from erosion. As the investigation progressed with a particular study of stable beaches it became evident that these, too, were subject to temporary displacement of beach material, according to the prevailing weather conditions. Thus it was possible for a generally stable beach to be unstable at a particular instant with reference to the conditions at the time. In the reports which follow, an effort has been made to distinguish between the general and the particular, by using the word stable to indicate the general or long-term state of the beach and the word equilibrium where the more scientific interpretation is required. Usually, in the latter case, the beach is described as being in equilibrium 'with respect to some particular circumstances'. Both words imply that there shall be no mass movement of beach material away from the beach. It will be observed that the first condition of stability is concerned with the movement of material up and down the beach between high- and low-water mark, and in nature such surface movement is continuously taking place in order to make up any irregularities which may have occurred, and to maintain the appropriate slope of equilibrium. The latter condition in a similar way is concerned with the movement of material longitudinally along the beach, in the establishment of the arc of equilibrium, but once this has been formed the beach becomes stable, and further movement ceases. What, then, is the relationship between mass movements of beach material and the circumstances of wind and wave, which are known to be the cause? These occur because changes in wind and wave produce changes in the orientation of the beach, to the accompaniment of mass transportation of material in a manner which will be described; but first it

is apparent that some attention must be given to the mechanism whereby such transportations are effected. The wave is the usual medium of transportation. A careful study of the form and nature of waves is therefore a necessary preliminary to an investigation into the causes and character of beach movements.

Transportation of Beach Material by Waves.

Waves are usually produced by wind; the frictional drag of the moving air upon the surface of the sea imparts to the top layers of the water a fraction of its energy which is sufficient to create upon what would otherwise be a placid surface, numerous hillocks of water. These eventually coalesce to form larger hillocks, and also take form to become the rollers with which all are familiar, and which should not require further description here. These rollers then speed on their way obeying their own complex laws, independent of, but nevertheless still modified by, the wind which created them. Experimental investigations and mathematical analyses have been carried out into the nature of these waves, but for the present it is sufficient to understand that they are reservoirs of that energy which was originally imparted to them by the wind. This energy is capable of exerting force, and doing work on any physical obstruction which the wave may happen to strike, and is responsible for the transportation of beach material. When a sea wave or roller expends itself upon a shingle or sandy beach the kinetic energy with which it is charged imparts movement to the particles in association with it so that a portion of them are rolled up the slope of the beach and work is done upon them against gravity. With the receding flow of water, however, they are carried down the beach again, and so the slope of equilibrium is maintained, and the location of the beach material is basically unaltered. When the direction of travel of the wave crest is normal to the contour of the beach, movement of the pebbles is confined to this up-and-down movement and there is no sideways or longitudinal displacement of beach material. When, however, the wave strikes the shore obliquely, the sideways component of its kinetic energy exerts a pressure in a longitudinal movement or drift. For complete stability of a beach, therefore, which implies that there shall be no mass longitudinal drift of beach material at any time, a condition must be that the waves shall strike the beach normal to the shore line. In other words, they shall not have a sideways component in their velocity of approach. This is the basic law of stability.

The Influence of the Sea Bed on the Direction of Waves.

The controlling feature in the disposition of beach material is thus the direction of approach of the waves as they make contact with the beach. What, then, are the controlling features of the waves themselves which influence the direction of their travel? Attention is drawn to the evaluation of the velocity of an ocean wave, which has been computed mathematically. The expression which gives the velocity of propagation of an ocean wave is as follows:

$$c^2 = gh \qquad \text{(deep water)}$$

$$\text{or } c^2 = g(h + 3y) \qquad \text{(shallow water)}$$

where c = mean rate of propagation
g = acceleration of gravity
h = mean depth of channel
y = elevation of wave.

It will be apparent that the velocity of such a wave is related to the depth of water in which it travels, being greater in deep water than in shallow. Moreover, a wave travelling over a sea bed of irregular depth will suffer deformation and the wave crest will be held back in shallow water and speeded up in deep. In practice the sea bed varies in depth and, generally speaking, it gets deeper the farther away it is from the shore. It would not be far from the truth if it were assumed that the sea bed could be represented by a uniformly-inclined plane penetrating deeper into the sea from the shore line; and the deformation which would be produced on a wave crest by such a configuration would bear a close resemblance to actuality. A wave advancing in the direction of the shore directly up such an inclined plane would be travelling into shallower water and would, therefore, be slowing down; nevertheless, all points along the wave crest would at all times be over an equal depth of water and would, therefore, be travelling at equal speeds. Under these conditions, therefore, there would be no deformation and the wave crest would remain parallel to the contours of the sea bed and the shore line. It is apparent, therefore, that deformation of the wave crest would only occur when different points on the wave crest were travelling over different depths of water or, in other words, when the wave was travelling obliquely aoross the slope of the sea bed. In order to illustrate how the wave crest would be deformed under such conditions, an extreme case has been examined mathematically where an imaginary wave has been considered to be travelling at the moment of initiation in a direction parallel with the contours. The results of this analysis are given in Fig. 2. This diagram is intended to represent a uniformly-shelving sea bed where the depth of water is proportionate to the distance from the shore, and where on account of this the velocity of propagation of the wave crest is related to this distance by the expression $c^2 = gh$. It is then imagined that a wave is artificially produced with its crest starting at the shore and stretching an arbitrary distance between nought and infinity along a line normal to the shore such that its direction of motion at the time of origin is parallel with the shore. The object of this analysis is to examine the shape of the wave crest, at regular intervals of time after propagation, and to follow the track of a series of points on the wave crest. It is presumed that the formula for the velocity is $c^2 = gh$ for simplicity; as the more exact formula $c^2 = g(h + 3y)$ would introduce unnecessary complications. It is hoped that the figure will prove self-explanatory and will demonstrate how, under these conditions, the profile of the wave crest is altered and the direotion of its travel is modified.

In practice, waves in deep water may be approaching the land from all angles, and provided information is available as to the configuration of the sea bed their paths may be computed mathematically as in the particular case described above. Without undertaking this task, it will, nevertheless, be apparent that in all cases they will finish their journey by breaking normal to the shore line. The shelving under-sea bed will have guided them inwards towards the shore, in the manner described in the first lines of this section. It is necessary to carry the matter a stage farther and consider the implications of this natural phenomenon. It would be in order, for instance, to declare that in windless weather all waves breaking upon a beach are constrained in the manner shown to advance towards the shore to strike it normally. Earlier in the Paper it has been stated that a requirement for stability of beaches shall be that very condition The implication of the two statements taken together is that beaches should always be stable, and one must reconcile this conclusion, with the undoubted facts of nature, that they very frequently are not. The qualifying and important condition upon which the truth of the above statement depends is inherent in the phrase 'windless weather' because the wind is able to modify wave motion and to impart a longitudinal or sideways component to its velocity at its point of contact with the shore.

The Effect of Wind.

The orientation of a beach is understood to mean the direction in which the beach faces, and it will at once be perceived that this feature cannot remain unconnected with the circumstances of wind and tide applicable in the area. The subject will be discussed first with reference to those localities which have a soft sea bed, and where the 'arc of equilibrium' will have taken shape. In such a case the orientation could be denoted by an axis bisecting the beach and passing through the centre of the circle of which the arc forms a part. Over centuries of time a state of overall stability will have been established in a beach such as that described above because the orientation will have adjusted itself to prevailing weather conditions and the movement of beach material by daily variations in climate to the left will have been compensated by movement to the right. The incidence, however, of a strong cross wind would temporarily upset this stable configuration and, by imparting to the waves a longitudinal or sideways component of velocity, would immediately render the whole stretch of beach unstable with respect to those particular conditions. A longitudinal movement of beach material would then take place in the direction of the wind; a denudation of the beach would occur on the windward end of the beach; and an accumulation would appear on the leeward side. The effect of this redisposition would be a tendency towards the re-orientation of the beach to suit the new conditions, and this phenomenon would involve a displacement of the axis of orientation by an angle of shift, and the establishment of the 'arc of equilibrium' in a new position. If the strong cross wind were to be sustained for sufficient time, and other factors permitted, the displacement would be sufficient to re-form the beach in its new orien-

tation and once more to re-establish equilibrium with respect to the new conditions. The appearance of a strong cross wind would also bring about a change in the basic structural stability of the beach, which influences the process whereby the adjustment is carried out, and introduces an elaboration to the simple movement sideways of the beach material. Fig. 3. is intended to represent the arc of equilibrium of a stable beach which has been made temporarily unstable by a cross wind. The angular shift of the axis of orientation has been indicated together with the new configuration of the beach which would be stable under the new conditions. This diagram could also represent

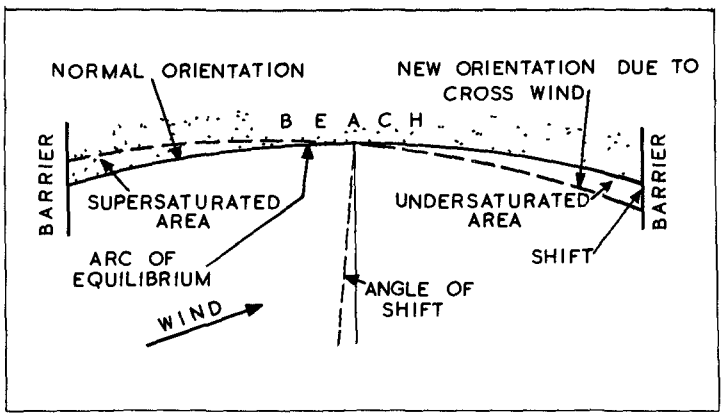

Fig. 3. Diagram showing how a strong cross wind produces re-orientation in a stable beach together with associated beach movements.

a section of beach between two groynes; thus it will be readily appreciated that this matter will have an important practical application in the engineering science of coast protection. The first curve in the diagram represents the stable configuration of the beach initially with respect to average conditions, and the second curve represents the configuration appropriate to the new conditions, involving a strong cross wind from left to right. It will be observed that during the process of re-orientation a triangular-shaped area of beach to the left of the axis has lost stability or become, as it were, supersaturated with beach material. This material cannot support itself under the new conditions, and the effect of this in nature is that it is rapidly drawn down by the waves, and slumps to form a shapeless accumulation in the vicinity of low-water mark. From this position the gradual sideways movement described, takes effect until all this superfluous material has been transferred to the other side of the axis, where there is a corresponding triangular area which is deficient in material or 'undersaturated'. The filling-in of this area restores the curve of equilibrium, but with changed orientation.

Shift of the Axis of the Arc of Equilibrium.

The long-term or average orientation of a beach is, therefore, the cumulative effect of all winds which have blown in the locality over the centuries. It could also be regarded as an average effect of winds unless major climatic changes are being experienced. The

day-to-day orientation may change, producing displacements in the beach material, but these are compensatory in character, leaving the general configuration the same. Nevertheless, seasonal changes in the orientation do occur to suit the change in the direction, intensity and duration of the winds in the area, due to the seasonal cycle of the year. It should be appreciated that re-orientation involves the transfer of beach material from one end of the beach to the other, which, of course, would be a much bigger operation in the case of a long beach than in a short one and the time taken would be proportionately larger. The strength and duration of winds blowing consistently from one direction are not always sufficient to transfer enough material to complete the re-orientation of a beach unless it is a very short one indeed, and usually the process is interrupted and reversed by a change of wind. With long beaches a small shift or re-orientation is possible only on a seasonal basis where, for instance, the prevailing winds during the summer season are different from those in the winter. With very long beaches such as the Chesil Bank even a small trace of re-orientation could be produced only by a major climatic change in the direction of the prevailing winds. Change in orientation, however, is a common feature in short beaches, and in the case of groyne systems where each section between groynes is considered as a separate and distinct beach it is a factor which must be taken into account and provided for in the design of the groynes. Where the groynes are spaced at short intervals, a single storm may completely re-orientate the beach, and similarly a following storm from a compensatory direction may re-establish the arc in its original position. It is a matter of considerable practical importance, particularly where the design of groyne systems is being considered, to establish the limits within which the orientation of a section of beach will be confined, under all the weather conditions which are likely to be imposed upon it. This is a factor which depends upon local conditions to some extent in so far as the nature of the prevailing winds and their direction have to be considered, and it would not be strictly correct to endeavour to apply a general formula to all cases. It is nevertheless the case that the length of the beach is the overriding factor which controls the probable degree of shift, and accordingly it is possible to establish an approximate relationship between the two which can be applied to problems involving this feature without a large error being incurred. The value of such a formula in practice more than makes up for the small degree of inaccuracy to which it might be subject. It is considered that shift may vary from an angle of 10 degrees in a short beach about 200 feet long to 2 degrees in a beach 4000 feet long.

Effect of Reflected Waves on Beach Configuration.

It may be taken as a general rule that any external agency which affects the direction of approach or configuration of the waves will be represented in the contour of the beach. The most important of these is the configuration of the sea bed to which may be added the effect of a reflected wave from some physical obstruction near the beach. When a wave encounters some structure such as a breakwater or harbour arm which juts out into the sea, it may, according to its direction of approach, be reflected in much the same way that light is reflected in a mirror. As it pursues its way after contact, in the changed direc-

tion, it then encounters the beach at a different angle to its fellow unreflected waves, and the beach material is arranged and moved until it faces the oncoming wave. The visual result is that the curve of the beach is likely to make a sharp reverse curve in the vicinity of such an obstacle. An example of the way in which a reflected wave influences the adjacent beach may be seen at Folkestone, where waves encountering the harbour breakwater are deflected on to the beach in the manner described and the curve of the beach is affected accordingly. On a smaller scale groynes have a limited local action and often produce a small reverse curve in their immediate vicinity. In some cases this may be due to reflected waves from the groyne, but it should not be forgotten that any kind of agitation or turbulence in the water produced by the waves encountering an obstacle on the beach would have the same result. Another occasion when deformation of the wave crest is mirrored in the configuration of the foreshore is when diffraction occurs due to the presence of some off-shore rock, island, or bank. When a wave advances towards the shore and encounters such a feature it naturally splits into two, and the two sections may continue towards the beach, in a very much altered form. This modified form then becomes impressed upon the material of the beach and produces appropriate configuration. Usually such a curve is opposite in character to what has previously been described as the "Arc of Equilibrium", and so it has been given the name "Reverse Curve". It may be found that long lengths of soft coastline, which may at first sight appear to be of irregular contour and therefore unstable, may in many cases be split up into a series of alternating "Arcs of Equilibrium" and "Reverse Curves" and in such configuration could be stable. In Nature it will be found that whereas the "Arc" may be of considerable length, the "Reverse Curve" is usually short and acute.

Although the natural equilibrium of the foreshore, established after many thousands of years, has in many cases been interrupted and distorted by sea walls, harbour arms and other artificial devices, such that it will never be restored to its natural shape and beauty, there are still many miles of untouched and unspoilt beaches which may still be preserved intact, providing that sufficient interest towards that end is established now. It is of great importance that effective control of the diminishing asset of the beaches should be instituted at once before the sands have all run out.

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