SECONDARY SAND TRANSPORT MECHANISMS

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INTRODUCTION

The basic concept of coastal littoral drift consisting of a "river" of sand driven by the direct alongshore component of oblique waves has long been considered as a basis for littoral transport equations. This concept however is highly simplified since the actual littoral drift on real beaches represents only the final result of the inter-action of dozens or perhaps hundreds of secondary hydraulic processes which continuously occur in Nature. On many Coasts littoral transport is taken to represent the primary mechanism of beach recession or build-up but many of the secondary mechanisms themselves are only partially understood and their individual contributions to the primary process largely unexplored. This paper therefore discusses some of these secondary processes and since off-shore-onshore sediment transport is probably the most important of these a mechanism for this transport mode is suggested based upon the interaction between wave energy and a work capacity parameter for the beach sediments.

GEOGRAPHICAL FACTORS

In considering a coast in plan view many factors that might loosely be described as geographical are readily observed. Headlands and groynes generate complex hydraulic phenomena. Such "hard" surfaces not only generate re-alignments of the sea-bed sediment but they also discharge rip currents and shed vortices which may carry large volumes of sediment to distances exceeding a kilometer out to sea.

Creeks and river discharges may also behave as groynes with the tidal discharges into and out of the river acting as a hydraulic barrier "jet-stream". The barrier effect of tidal jets can be such that Nature must form extremely large delta deposits at the tidal outfall zone offshore of the beach before littoral transport can function within an effective combination of attenuated jet velocity, water depth and wave breaking energy.

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A further obvious plan-form phenomenon of beaches, particularly within the unstable responsive state between fine weather small wave steep profile and high storm energy flat profile beaches is the development of cuspate beach shapes at the water-aerial beach interface i.e. stages 2 to 5 of the Short Model (Ref 1). The hydraulic processes which generate these beach forms must be highly complex but they clearly must exert a profound effect on long shore littoral transport. Much evidence is beginning to emerge that suggests that sand transport occurs in slugs or pulses and cuspate shapes have long been observed to migrate in the direction of the littoral drift as of the time.

Under long-shore transport conditions rip-currents become dominant hydraulic features of a beach during its cuspate shape development and such currents have a dominant effect on beach cell water re-circulation and offshore sediment transport. In addition the inception of cuspate topography leads to highly variable angles of incidence by the breaking wave even to the stage that any average or dominant angle of wave attack becomes meaningless under these circumstances. Nevertheless nett littoral sand transport from cuspate beach cells has been detected by tracer experiments and the driving force must consist of only the total hydraulic leakage from the cell. Clearly much study remains to be carried out on littoral transport on cuspate beaches.

BEACH NORMAL PROCESSES

The most significant variability in beach response to energy input is clearly demonstrated by the hour to hour and day to day fluctuations in cross-sectional profile. The onshore-offshore movements of beach sediments call into motion much greater volumes of material in the short term, by a factor of many magnitudes, than those that can be measured as alongshore transport. If, as it seems likely, the actual littoral transport represents only the longshore component of onshore-offshore sediment movement under oblique wave energy input then it would seem essential to study the onshore-offshore processes in their own right before even addressing the ultimate problem of calculating littoral transport. It is for this reason that beach normal or onshore-offshore processes are considered as secondary mechanisms in this discussion.

SEDIMENT WAVE INTERACTION

There must certainly exist a profound but predictable interaction relationship between wave energy input and the behaviour of beach sediments. Waves change the beach shape and sediment distribution across the beach but the converse must also hold true, the behaviour of the beach sediment changes the form, shape and breaking behaviour of the waves. Beaches change slope according to wave height, offshore bars develop that induce multiple wave breaks and wave reformations with increasing size of deep water wave but why do these processes occur? Why do small swell waves generate a steep beach whilst great storm waves generate wide flat slopes? Why indeed do beach sediments exist at all? If waves destroyed energy entirely by hydraulic mechanisms the world's coast would surely all be rocky shelves. Beach sediments demonstrate a highly developed mobility in response to incident wave height, and to a lesser degree tidal variation, and it has long been taken as a basic tenent that the larger the beach particles the steeper the beach for the same wave input.

Clearly the properties of the beach particles themselves must exert a highly significant effect on the behaviour of any beach which cannot be explained by considering the properties of the waves in isolation, both form part of a highly sophisticated mechanism designed by Nature to ensure the most efficient dissipation of energy with a maximum conservation of natural resources. Many detailed descriptions exist of beach profile and wave responses with the work of Short (Ref 1) and Wright (Ref 2) probably representing the most definitive(and fascinating) statement of what might well be called an "Atlas" of beach and wave geography. It is tendered however that until the interaction between sediment properties and wave mechanics are included such work will remain largely descriptive.

SEDIMENT POPULATIONS

Beach and river sediments apparantly exist in almost an infinite variety, to the extent that Nature seems to use whatsoever natural detritus that is available as of the place and the time and adjust the local geography to suit the energy demand of the ambient hydraulic process. Natural sediments do not consist of what might be described as "blocks" of particles all with the same properties but they occur in curious blends of all different sizes of particles from comparatively fine to comparatively coarse, all existing together within a finite volume.

Based on sediment grading curves as described in the literature, every natural beach sediment population contains a significant percentage of large particles and perhaps much more importantly an even more significant number of very fine particles. In normal grading analyses the "fine" contents in the "pan" are merely recorded for weight and thrown away but the fact remains that even on the most active beach exposed to the highest waves the largest particles found within the wave zone always contain a significant content of a matrix of fine particles dispersed within them.

It seems that Nature will never winnow out a sediment "blend" of particles to produce a neat-sized or gap-graded "mix", but always produces a full population encompassing the combination of a large number of particles over quite a wide range. Beach sediments thus exist and behave as integrated populations and not as groups of individual clusters of neat sized particles. It is perhaps for this reason that it is so difficult to calibrate model work carried out with sieved particles or beads almost all of the same size.

Because beach sediment populations are so wide a major difficulty is usually found in assigning some parameter that with describe the population, or its properties, in some meaningfull way and if possible provide some average index of the parameter that also has some competent descriptive power. Tradition has been to adopt a "size" parameter to describe particles using either a sieve train or a settling tube to arrive at a nominal "diameter" size parameter. Whilst settling tubes should be well superior to sieving tests in that at least the settling tube tests particles within an hydraulic environment nevertheless both tests have a low standard of accuracy and reproducibility and in fact should only be reliable when they test one particle at a time.

The two major sampling and testing variables are:-

(a) Both devices are extremely sensitive to feed rate, that is the number of particles being tested together at one time. In the mineral industry sieves can be made to selectively either pass or concentrate particular particle densities, shapes or sizes by merely varying the feed rate and the analagous problems with settling tubes have been well reported e.g. McNown and Pin-Nam Lin see (Ref 3).

(b) Secondly both devices "pass" or "settle" high aspect ratio particles in a highly preferential manner, in sieves these particles pass through the mesh end-on with their greatest dimension normal to the mesh whilst the same particles settle in water with their greatest dimension horizontal and usually demonstrating some flutter or oscillation as well.

Finally in a settling tube the particles must settle under Laminar flow and surf zone dynamics must always be turbulent. It would not be surprising therefore if sediment transport equations based on some nominal size derived from either of these two tests display such wide scatter and poor correlation. The problem must result from the shape factors of the particles together with a significant contribution from their surface texture. By analogy to basic aerodynamics it might be expected that particle shape and aspect ratio might represent almost the dominant transport and drag mode and a preliminary appreciation appears to confirm this proposition for water as well. The most simple parameter available that quantifies any particles shape factor and weight is its specific surface - that is its total surface area divided by its weight. In mineral technology the term used is F and for normal beach particles the unit of mm^2/ gram appears the most convenient.

Experiments carried out on a hydraulic spiral mineral separator under completely random turbulent input demonstrated that the migration of particles into high, medium and low energy zones across the spiral cross section was very strongly related to the particles specific surface and barely correlated at all with either sieve or settling tube diameters. It seemed therefore that the parameter of specific surface held much promise of providing a particle's energy response or work capacity indicator.

A most fortuitous discovery that when natural beach sediments are classified by particle specific surface is that the population is almost exactly Log-normal (See Fig 1) a property of sediments that has long been postulated but seldom detected by normal sizing methods. Intuitively the selection of specific surface to classify a particle seems reasonable also in that at least it provides a systematic integration and description of a particles properties of shape, texture, aspect ratio, specific gravity and thus weight and perhaps a good starting point for considering its overall hydraulic properties. In particular with a log-normal population distribution the ease with which borrow and native

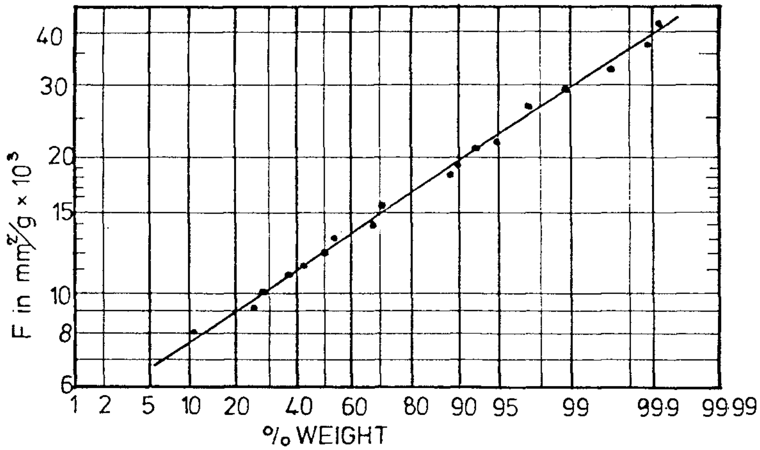

FIG.1 — SPECIFIC SURFACE : LOG PROBALITY DIAGRAM FOR ONE SAND SAMPLE

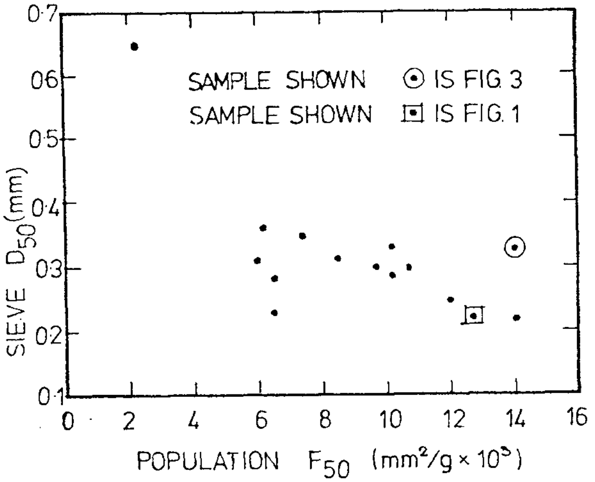

FIG.2 — COMPARISON OF D_{50} ~ F_{50}

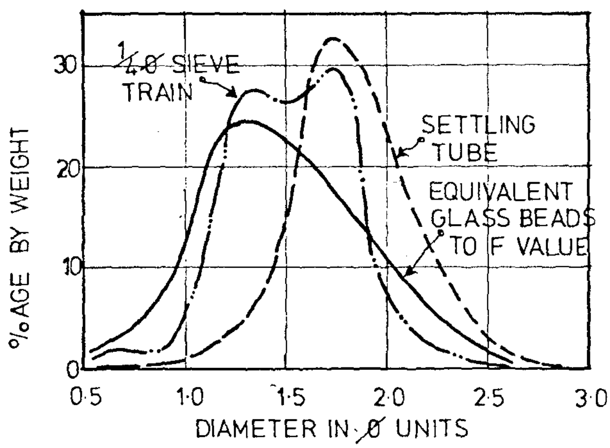

FIG. 3 – COMPARISON OF DIFFERENT PARAMETERS USED TO DESCRIBE SAME SAND SAMPLE

beach sands may be compared without recourse to deviation, skewness and kurtosis measures for example is also attractive.

As an indication of the absence of correlation between specific surface and sieve or settling tube diameter Fig 2 shows a plot of F50 against D50 for fifteen natural sediments taken up to 800 km apart on the Australian seaboard and Fig 3 shows a comparison of population diagrams as displayed by ¼ Ø sieving, settling tube and specific surface for the same sediment. Because specific surface cannot be plotted on the same graph as d or Ø units the specific surface population has been shown as the size distribution for the actual sediment's F value converted to percentages of various sized purely spherical glass beads. The curve centroid offsets must be highly significant, and the bi-modal sieve population is typical of the local coast.

WORK CAPACITY

Because the parameter of specific surface does provide a log-normal distribution for natural beach sediments and thus probably close to representing a basic or perhaps the basic description of the particles it seems worth while to test this property with other basic parameters involved in fluvial mechanics. Unfortunately this is not entirely possible because most workers in the field have not recorded much in the way of shape factors for natural sediments and much work has been carried out with gap-graded or artificial particles, neither of which are found as populations in Nature.

However several workers have analysed parameters with large amounts of data generally using natural sediments and the larger the data-base the more reliable should be the average properties. For considering transport of sediment on beaches perhaps the two most significant parameters to consider might be the critical scour velocity and the critical tractive force. For the first case taking the boundary graph between erosion and transportation from the Hjulstrom diagram (Fig 4a) and making some reasonable appreciation of a shape factor the famous hooked curve can be re-plotted as Fig as $\bar{\mu}$ against F. If it is accepted that particles below approximately o.1) mm dia as measured by sieves are in the silt range and entering the realm where water attraction and perhaps Van de Wals forces cause many particles to flocculate and behave as agglomerates the new graph, now straight lines, generates two branches when this zone of particle size is reached. Of more interest perhaps the relationship between critical scour velocity and specific surface appears to be quite close to:-

$$\bar{\mu}_{crit.} = \frac{k_1}{\sqrt{F}} \qquad \text{.....} \; (6.1)$$

In a similar fashion if the vast data array presented by Lane (1953) is similarly re-plotted to substitute F instead of D (see Figs 5a and 5b) there again seems a reasonable approach to:-

$$\tau_{o\,crit.} = \frac{k_2}{F} \qquad \text{.....} \; (6.2)$$

If the relationship of equation 6.2 can be substantiated within a reasonable envelope then the criteria of the threshold of a critical tractive force might be considered

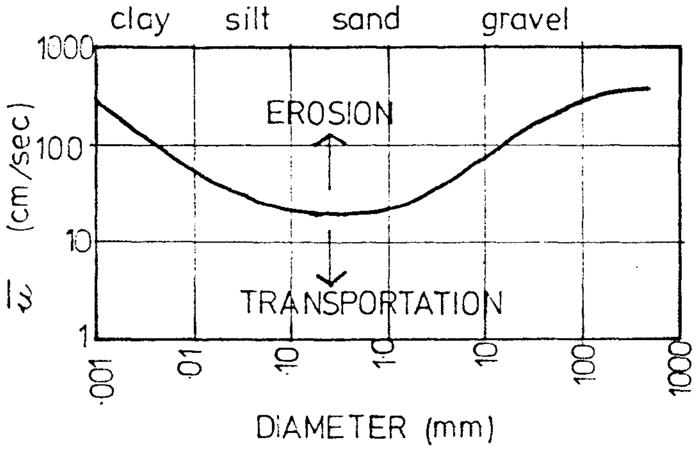

FIG 4_A – HJULSTROM DIAGRAM (1935)

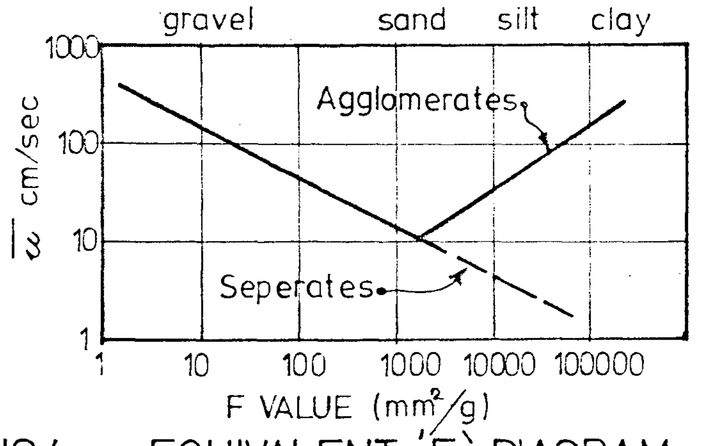

FIG.4_B – EQUIVALENT 'F' DIAGRAM

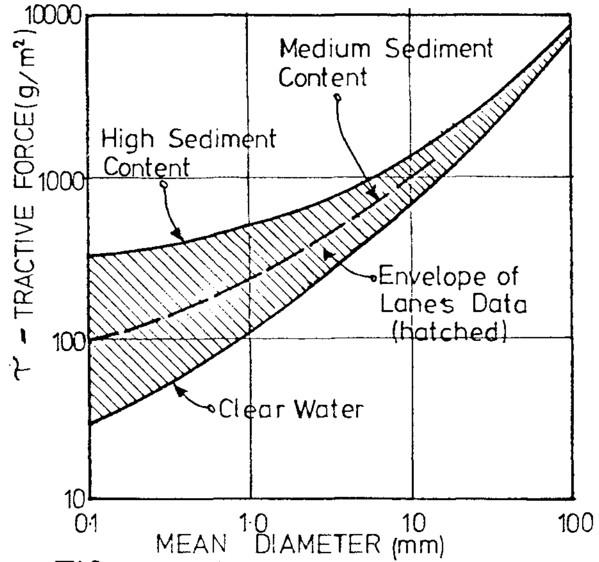

FIG. 5A – ADAPTED LANE DIAGRAM (1953)

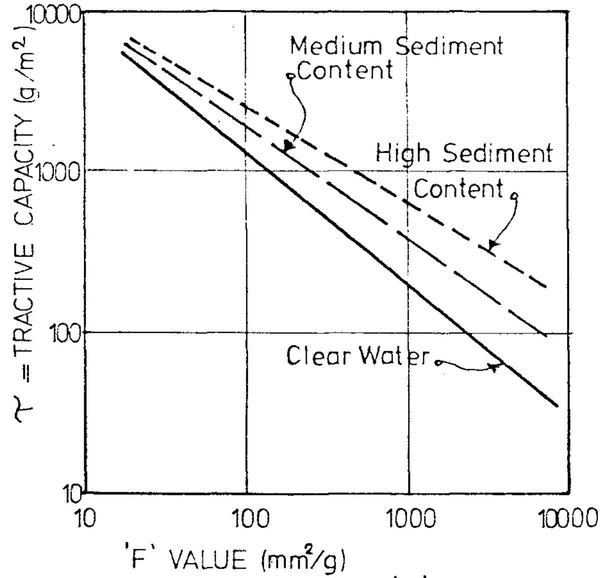

FIG. 5B – EQUIVALENT 'F' DIAGRAM

as a measure of a particle populations ability to withstand hydraulic work input up to the stage where the particles are displaced and put entirely into suspension. If this concept is viable then τ_o will represent the maximum work capacity of the sediment provided conditions are turbulent.

In Nature wave energy dissipation is a most complex phenomenon but suppose that the extreme case is considered, this being when the total average wave energy for one wave is completely absorbed by the active sediment volume of the beach. Further if it is assumed that a particular active volume of beach sediment multiplied by its average critical tractive force is required to absorb the total energy of the wave without washing away then:-

$$\text{Sediment Volume} \times \tau_{Av.} = \frac{\rho g H^2}{8} \qquad \text{..... (6.3)}$$

which reduces to:-

$$\text{Vol} = K_3 F H^2 \qquad \text{..... (6.4)}$$

this being for one wave. However in Nature some wave energy is dissipated by the breaking mechanism, some wave energy is reflected, some is deflected by currents, wind, hydraulic interference and suspended sand loadings so perhaps the best that might be expected under real conditions is:-

$$\text{Sediment Volume} \propto F H^2 \qquad \text{..... (6.5)}$$

These approximate equations can only be considered for a simple case, in particular a wave break perfectly parallel to the beach and no rip currents or littoral drift but they may well allow for a crude first step model of onshore-offshore beach behaviour.

It would follow however that the higher the work capacity of the beach sediments the smaller the volume of sediment that would be required to absorb the same wave energy, therefore the lower the F value of the particles the steeper the beach for a constant wave climate, all very much as is always observed.

THE WORK PRISM

A question apparantly seldom addressed is "how" do beach sediments in fact absorb wave energy? It can certainly be seen that they do - but how? It is straight forward to deduce that if all sediment transport and volumetric re-adjustment is caused purely by sea-bed current tractive forces raising sand into suspension or as semi-suspended bed load then the thickness of the mobile bed must be extremely thin, often quoted as only a few grains in thickness. However recent work on beach tracers e.g. Chapman (Ref 4) and the consideration of the swept prism e.g. Chapman & Smith (Ref 5) has clearly demonstrated that on real beaches a vast volume of upper beach sediment extending to depths of at least 3 metres during storms turns over and/or intermixes continually representing a remarkably large active volume. Even under quite mild conditions with waves not exceeding 2m. high tracer grains have been recovered from depths exceeding 1m. below the beach surface on both Sydney and Gold Coast Beaches.

On the one hand it would seem absurd that a layer of sediment only a few grains thick on a beach could absorb any wave energy at all, yet how can the extremely large three dimensional movements and re-mixing of real beach sediments be explained. Beaches are traversed by waves and waves result in a variable hydraulic head pressure being exerted on the sea-bed. These fluctuations of hydraulic head will be followed by a variable hydraulic pore pressure within the sediment that composes the sea-bed. In its simplest case as a wave approaches a given sea-bed zone the inter-particle pore pressure will increase and once the wave has passed the pore pressure will reduce. This reduction in pore pressure will introduce an upwards vector of pore

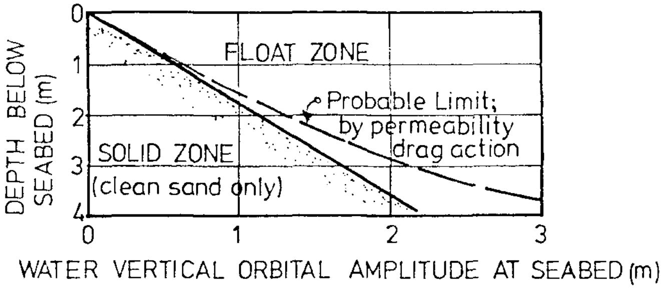

FIG.6- PORE PRESSURE INDUCED FLOAT ZONE

pressure and for the sea-bed sediments to remain at rest the shear strength of the sediments must exceed the pore pressure released stress. The most elementary equation for the development of "quick" conditions in purely frictional sediments is:-

Pore pressure $\mu >$ soil shear strength τ .....(7.1)

and for critical stability:-

$$\mu = \tau = (\rho_s - \rho)\ h\ \mathrm{Tan}\ \phi \qquad .....(7.2)$$

It is straight forward hence to construct a graph of pore pressure release against submerged sediment shear strength and a typical example is given as Fig 6. In the context of the graph the amplitude of pore pressure release may be taken as the wave height close to the breaking zone or the vertical amplitude of the orbital water movement for deep water conditions. Clearly the drag on hydraulic pressure transfer due to the permeability of the sediment population will decrease the depth of what is shown as the pure "float zone" and modified by the nominal only dashed line. The depth of sediment that is called the float zone need not of course go completely "quick" in the soil mechanics sense but even the vertical movement of only a few grain diameters of the total dead load of the float zone would absorb a great deal of dynamic energy in lifting it. Moreover a vertical movement of the sea-bed beneath a wave of the small amplitude postulated and within the short time scale involved would barely be noticed by an observer provided of course that he could hold his feet whilst the wave passed over him.

It might well be reasonable therefore to suggest a first approximating crude model of the energy absorbing mechanism of a sediment beach. If the sediment population has a finite and maximum capacity to absorb energy before it is washed away, if the cross sectional volume of the sediment population can be equated against wave energy input and the depth below the beach surface or seabed within which the sediment absorbing capacity may be called into action then it is possible to estimate what might be called the work prism of a beach that might be stable under any given wave energy input. What is here described as the work prism applies to each wave individually but the envelope of all work prisms on a beach may be represented by the swept prism concept described in Ref 5.

On real beaches some sediment is put into suspension and transported as such by even modest waves in the breaking zone but the rate of transport and the transport distances are often remarkably small and the phenomenon may even represent the inception of a beach slope adjustment. In great storms however vast volumes of sediment are placed in suspension but because of the great complexity of the hydraulic processes involved this factor has not been included in the simple model under consideration. The basic model is thus postulated largely for long term non-storm average conditions.

BEACH PROFILES

If a beach sediment has a maximum and limiting work absorbing capacity then an increasing wave energy input will demand a larger volume of the same sediment for equal wave dissipation. Since the thickness of the sediment work prism is not markedly sensitive to wave height and permeability must have a limiting effect on the thickness then the only way that more sediment may be called into play is to extend the prism in width across the beach and in Nature this can only be done by flattening the beach slope. The similarity to the concept of KD values for non-interlocking armour units might be noted.

As a first approximation therefore the hypothesis is that beach slope and width will be proportional to incoming wave energy. There must however be a critical slope beyond which the toe of the work prism is unstable and at this stage since most of the sediment in the prism will have reached its maximum work capacity already then all, or most, of the prism will liquify and flow offshore until it reaches a water depth where the energy input is again less than its maximum work capacity. This provides an explanation for the formation of offshore bars and demonstrates another of Natures methods of conservation of resources because the development of an offshore bar causes the bigger incoming waves to break further offshore and the inner beach merely re-adjusts with a profile compatible with the reduced energy of the re-formed wave and on the beach the cycle may now be repeated. The generalised descriptive model of the proposed mechanism is shown in Fig 7.

This mechanism may also explain why the inner beach accretes during fine weather small swell conditions. In a simplified form, if say during a mildly variable wave energy input:-

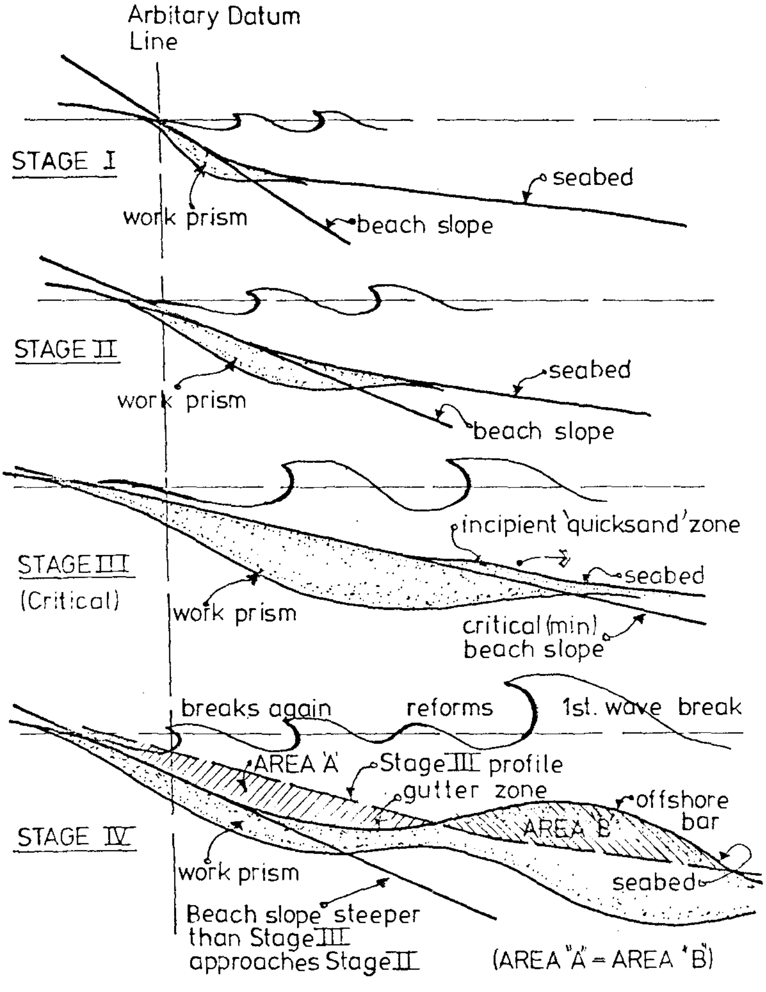

FIG.7—RESPONSE OF BEACH PROFILE TO WAVE HEIGHT INPUT FOR CONSTANT BEACH SAND

(a) The beach slope left by the previous wave is flatter than critical any sediment mobilised by the next wave will push up thebeach to steepen it

(b) If the beach slope is existing at critical slope there will be no change

(c) If the beach slope left by the previous wave is steeper than the critical slope for the next wave then the slope will flatten and sediment will migrate offshore.

This simple model applies strictly on an individual wave basis, so that spectural and statistical measures would need to be applied to the wave climate before it might be possible to assess whether the model is reasonably valid in practice.

BEACH SORTING

A further process of considerable significance concerns the natural phenomenon of sorting on real beaches. Concentration areas of various apparant size fractions can readily be observed on beaches and there is much evidence to suggest that high energy particles tend to concentrate in high wave energy zones and vice versa. It would be only reasonable to expect Nature to apply resource conservation in this manner and optimise the total work capacity of the work prism by selective sorting and a similar mechanism might be expected for zeta bays where wave energy varies along the plan profile of the beach.

However within the concept of a total cross sectional work prism this sorting might well be considered as a microprocess existing as a dynamic internal fluctuation within the prism as depicted in Fig 8. The general discussion here considers average wave energy equated to the average work capacity of the prism and internal sorting within the prism might well then be represented by an extra efficiency factor that is greater than unity. It may even be that this internal sorting together with the localised humps and hollows that thus form within the beach profile, particularly on models, merely represent local variable fluctuations within an overall average beach slope and accordingly might be simply regarded as local "noise" impressed upon a general trend.

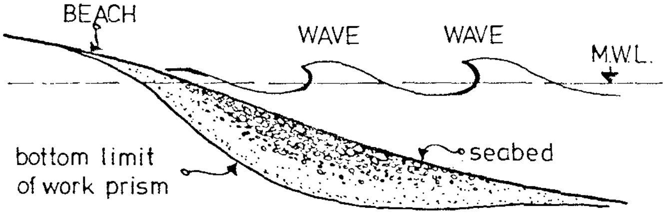

FIG. 8 – DIAGRAM OF MICRO-SORTING OF SAND WITHIN WORK PRISM
(LOWER 'F' VALUE DEPICTED BY LARGER PARTICLE)

If all the mobile sediment remains within the outer limits of the maximum work prism for the worst ambient wave energy then there has been no beach erosion, merely a cross sectional re-adjustment and as observed by Chapman (Ref 4) the appearance of the visible beach tells nothing about the work capacity of the total system, the real action always happens beneath the sea surface. The consideration of nett losses from the work prism into dunes, into offshore sinks and as littoral transport is of course another consideration to those discussed above.

CONCLUSION

(1) Secondary beach processes of remarkable complexity operate on natural beaches in both the micro and macro scale generally simultaneously such that it is extremely difficult to isolate the overall effects of each or assign their individual contributions to either beach stability or littoral transport.

(2) Many of these secondary processes are briefly discussed and for onshore-offshore transport in particular preliminary suggestions are made for modelling beach profiles not from wave data alone but from the interaction between beach sediments and wave energy following the application of a work capacity parameter to the sediments themselves.

APPENDIX - REFERENCES

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