BEACHES: PROFILES, PROCESSES AND PERMEABILITY

Michael R. Gourlay

Department of Civil Engineering
University of Queensland, St Lucia, Australia.

Abstract

Equilibrium beach profiles have been investigated in the laboratory for two beach materials, 0.22 mm marine sand and 1.55 mm crushed coal. Analysis of the results confirms that the dimensionless fall velocity H_o/Tw is an important parameter influencing both surf zone hydraulics and the form of the resulting equilibrium profile. Beach permeability also significantly influences the hydraulics within the beach face and it has been found that both H_o/Tw and the parameter w_f/w, the ratio of the fluidising velocity to the fall velocity, influence the form of the equilibrium profiles of permeable beaches.

1. INTRODUCTION

The problems involved in the interaction between waves and beaches are complex and while much research has been undertaken in this field, it is still not yet possible to predict on empirical grounds, let alone theoretical grounds, the shape of a beach after it has been subjected to given wave conditions. This situation applies both in the apparently simple two dimensional case where waves approach the beach with crests parallel to the shoreline and in the three dimensional case where matters may be further complicated by offshore wave refraction and geographical features such as headlands, rock bars, etc, as well as man made structures.

Investigation of this problem in the field involves an extremely complicated interacting system with many variables virtually none of which can be controlled. Moreover, the simultaneous measurement of all relevant variables over a sufficiently large area is in most cases completely impossible. On the other hand, investigation in the laboratory encounters problems concerning the reproduction of a sufficient number of the relevant variables in correct relationship to one another. Thus the laboratory investigator is confronted with the problems of scale effects and of too simplistic a representation of the phenomena. Nevertheless, it is possible in the laboratory to investigate certain aspects of beach processes in a systematic manner so that the general behaviour may be established. For example, the work of Kemp and Plinston (1968) has shown the significance of the surf zone condtions, as expressed in terms of the ratio of uprush time to wave period, in determining the interaction between breaker type and beach profile. Again, the general influence of the height of a sand dune upon the amount of shoreline recession during a storm has been established by van der Meulen and Gourlay (1968), confirming what had been suspected but could not be proven from available field data.

While laboratory investigations provide a means for gaining further understanding of beach processes under controlled conditions, the solution of many practical coastal engineering problems cannot wait until complete understanding of these processes is obtained. Consequently a second very important purpose of laboratory beach profile investigations is to compare the behaviour of various model beach materials at laboratory scale with prototype conditions so that model scale relationships may be established for the design of movable bed coastal models used in the solution of real engineering problems involving coastal sediment transport. It has been a common procedure to use lightweight sediments in such movable bed models on the assumption that, because these materials are more easily moved by the flow or waves in the model, they will reduce the influence of scale effects. It has also been long recognised that such materials often give grossly distorted beach profile shapes particularly on the beach face and in the surf zone. The investigation described in this paper began as a study of the use of crushed coal as a model beach material to represent natural beaches of quartz sand but subsequently developed into a more general study of the processes which determine the shape of beach profiles formed in beach materials with different permeabilities.

2. FACTORS INFLUENCING BEACH PROFILE SHAPE

A large number of factors influence the shape of beach profiles in nature. These may be divided into active factors and passive factors. The former produce the actions which mould the latter into a given profile shape. At the same time changes in the profile shape modify the mechanisms by which the active forces mould the profile. The following are the more common factors involved:

<u>Active factors</u>

- waves, tides, winds, rainfall, temperature;
- duration of influence of active factors.

<u>Passive factors</u>

- beach material, initial profile shape;
- geology and/or other constraints.

In practice most model investigations neglect the effects of tides, winds and rainfall and reproduce only the action of waves upon various beach materials. The constraints of geology and/or artificial constructions are usually not included in tests but are replaced by the constraints imposed by the model test basin. The latter at one and the same time may both exclude prototype three dimensional effects produced by nearshore oscillations and circulation systems and introduce spurious three dimensional effects characteristic of the model basin. Moreover, wave generators producing regular waves in shallow water also generate parasitic secondary waves which can affect the form of the beach profile (Hulsbergen 1974).

Even with the very limited number of factors normally considered in model tests, still further simplifications are generally made. Most laboratory investigations of beach processes have been made with regular waves of constant height and period. Only a few investigations have involved irregular and/or wind generated waves (e.g. van der Meulen and Gourlay 1968, Kraai 1969, van de Graaff 1977 and Vellinga 1978). While numerous tests have been made with both quartz sand and various light-weight materials of different median sizes, systematic tests of the effects of variations in the grading and shape of beach sediments are very few (e.g. Collins and Chesnutt 1975). Opinion is divided as to whether the slope (and/or shape) of the initial profile affects the shape of the final equilibrium profile although it is recognised that it certainly affects the time taken to reach equilibrium. The fact that water temperature cannot be controlled in outdoor model basins and often has not been controlled in indoor ones means that many investigators have had difficulty in obtaining equilibrium profiles with fine sands whose motion relative to the fluid, as expressed by their fall velocity, is significantly affected by temperature (Chesnutt 1975).

3. BEACH PROCESSES AND SURF ZONE HYDRAULICS

3.1 The Equilibrium Beach Profile

The equilibrium beach profile is that profile shape which when subjected to a given wave condition dissipates and/or reflects all the wave energy reaching it in such a manner that no net transport of the beach/bottom sediment occurs anywhere along the profile. The sediment transport mechanisms involved in this process are complex and vary in nature along the profile. For instance offshore of the breakpoint sediment transport is initiated and maintained by the orbital motion of the waves which exerts a shear stress on the bottom material through the oscillatory boundary layer created by the waves. The process is complicated by the development of ripples on the bottom and the occurrence of complex interactions between the oscillatory flow and vortices formed in the lee of the ripples. At the breakpoint relatively large amounts of sediment may be thrown into suspension, particularly by plunging breakers, and the flow becomes highly aerated. High aeration and suspension of sediment particles may continue within the surf zone as the bore from the broken wave travels landward. At the shoreline the uprush deposits its remaining sediment on the beach face as it percolates into the porous beach material before the backwash and/or outflow from the beach face mobilises the sediment again. The sediment transport processes acting to form the equilibrium beach profile are thus complex and cannot be related to a single simple model.

It has long been recognised that there are two basic forms of equilibrium beach profile (figure 1).

(i) The step profile or swell profile formed when the waves are of low steepness (H_o/L_o small) and/or the beach material is coarse.

(ii) The bar profile or storm profile formed when the waves are of high steepness (H_o/L_o large) and/or the beach material is fine.

The two profile types generally correspond with the concepts of reflecting and dissipative beaches as described by Short (1978). Transition profiles between these two limiting cases may exhibit rhythmic alongshore variations such as crescentic bars and beach cusps. In such situations the beach profile varies significantly in shape depending upon its location with respect to these rhythmic features.

Futhermore a bar profile may have one or more bars depending upon the wave steepness and/or the beach slope.

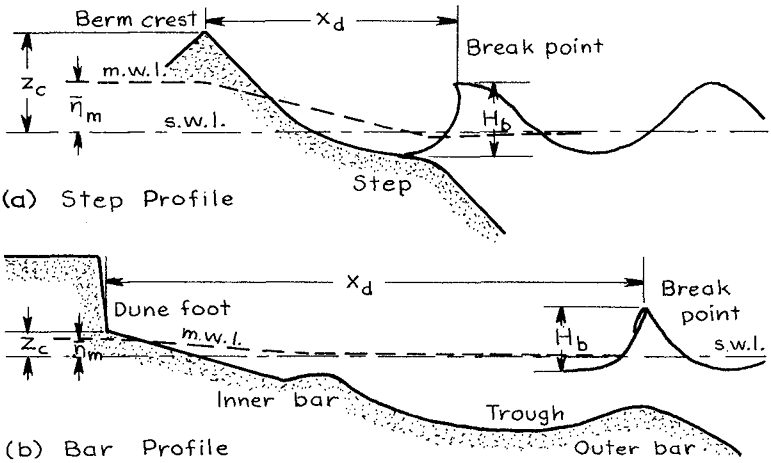

Figure 1

3.2 Diminsionless Fall Velocity H_o/Tw

In the search for model scale laws for beach process modelling, increasing attention is being paid to the use of the dimensionless fall velocity as a scaling parameter. For instance, Saville and Watts (1969) and Saville (1980) implicitly used this parameter in an investigation in which fine crushed coal was used to model larger scale beaches formed in fine to medium sand. Gourlay (1968) proposed the use of the parameter H_o/Tw for describing beach processes, pointing out that H_o/w represented "the time taken for a sand particle to fall a distance equal to the wave height. If this time is large compared with the wave period, any material stirred up by the breaking waves is likely to remain in suspension and to move as suspended load. If it is of the same order of magnitude or less than the wave period, bed load motion will predominate". Thus it was suggested that not only was the parameter H_o/Tw important in beach processes but that a value of the order of unity could be critical in determining the different sediment transport processes which lead to different profile forms.

Some time earlier Iwagaki and Noda (1962) had shown that the occurrence of the two main profile types, step profiles and bar profiles, depended upon the two parameters H_o/L_o and H_o/d. Bar profiles occurred at relatively large values of both parameters and step profiles at small values. Subsequently Sitarz (1963) showed that the profile type depended upon the following parameter:

$$\frac{H}{T\sqrt{g(s-1)d}} \quad \begin{array}{lll} < & 0.6 & \text{step profile} \\ > & 0.6 & \text{bar profile} \end{array}$$

with bar profiles always occurring if $H_o/L_o > 0.03$. This parameter is very similar to H/Tw since $w \propto \sqrt{g(s-1)d/C_D}$ where C_D, the drag coefficient of the sediment particles, is a function of the Reynolds number (wd/ν). Subsequently a number of researchers using data from various sources found that step and bar profiles could be separated on the basis of $H_o/Tw(d_{50})$.*

e.g.	Dean (1973)	$H_o/Tw \lessgtr$	0.85
	C.E.R.C. (1973) based upon Kohler and Galvin	$\lessgtr$	0.6 to 2.0 depending upon H_o/d
	Gourlay (unpublished)	$\lessgtr$	1.55 for fine sand (0.2 to 0.3 mm)
		$\lessgtr$	0.4 for coarse sand/ fine gravel (2 mm)

In the last case the critical value of H_o/Tw decreased with increasing sediment size, indicative of the possible influence of beach permeability on profile shape.

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* Unless otherwise specified the value of w used to calculate H_o/Tw is $w(d_{50})$, the fall velocity of the median sediment size.

More recently van Hijum (1974) found that for coarse material with $d_{90} \geqslant 6$ mm bar type profiles were formed when

$$\frac{H_o}{L_o} > 2.5 \frac{d_{90}}{H_o}$$

Assuming $C_D \simeq 1.3$ for coarse natural sediments and s = 2.65 this reduces to

$$\frac{H_o}{T\ w(d_{90})} \lesseqgtr 0.48$$

where $w(d_{90})$ is the fall velocity corresponding to the d_{90} size. In fact the beach material was very uniform and this relationship is probably equivalent to

$$\frac{H_o}{T\ w(d_{50})} \lesseqgtr 0.54$$

which is the same order as that established for coarse material from the present author's earlier unpublished analysis.

A change in profile type also implies a change in beach slope. Kemp and Plinston (1968) found that the beach slope was a function of $H_b/Td^{\frac{1}{2}}$ which parameter is essentially the same as that used by Sitarz. Kemp and Plinston used the breaker height which is a more relevant wave height than H_o when the mechanics of the actual surf zone processes are being considered. For small values of $H_b/Td^{\frac{1}{2}}$ the beach slope decreased as $H_b/Td^{\frac{1}{2}}$ increased up to a critical value, above which the beach slope was constant. They also found that the critical value of $H_b/Td^{\frac{1}{2}}$ at which the beach slope changed significantly corresponded to the transition from surging/collapsing breakers to plunging breakers which occurred when the relative uprush time T_u/T, or "phase difference" of the uprush, was 0.7. Subsequently Nayak (1970) found that both the beach slope and the reflection coefficient decreased with increasing values of H_o/Tw. Moreover, reflection was smaller for coarser beach materials with the same value of H_o/Tw, apparently because of the increased permeability of the coarser materials. More recently Dalrymple and Thompson (1976) using data from a number of sources found that the beach slope at still water level decreased with H_o/Tw for step type beach profiles but tended to become constant for values of $H_o/Tw > 1$ when bar profiles were present.

Considering the problem of model scale relationships for dune erosion during a storm surge, van de Graaff (1977) and Vellinga (1978) have found that beach processes may be modelled using very fine sand, if H_o/Tw has the same value in both model and prototype. If this criterion cannot be met, then it is necessary to distort the model profile scales.

3.3 Initial Beach Slope

There has been some difference of opinion as to whether the initial slope of the beach profile affects the final equilibrium profile shape. For instance Dalrymple and Thompson (1976) found that initial slopes from 1:5 to 1:10 had no significant effect upon the equilibrium shape of beaches formed form 0.4 mm sand. Similarly van Hijum (1974) found the same result for the same initial slope range when the beach material was fine gravel. Earlier Nicholson (1968) claimed a similar result for 2 mm quartz sand with initial slopes from 1:5 to 1:20. On the other hand, Chesnutt (1975) found that equilibrium beach profiles formed in 0.2 mm sand may be affected by initial profile slopes when the latter was changed from 1:10 to 1:20. Sunamura and Horikawa (1974) found that initial profiles of 1:10, 1:20 and 1:30 influenced the final profile shape formed in 0.2 and 0.7 mm sands and proposed that profiles be classified on the basis of whether they resulted in erosion or accretion of the original beach face. Recently Hattori and Kawamata (1980) combined this concept of eroding and accreting profiles with a parameter which includes both the initial beach slope and the fall velocity, i.e.

$$\frac{(H_o/L_o)\tan\alpha}{w/gT} = 2\pi\frac{H_o}{Tw}\tan\alpha$$

$$\begin{array}{lll} < & & \text{- onshore transport} \\ = & 0.5 & \text{- neutral (equilibrium)} \\ > & & \text{- offshore transport} \end{array}$$

It is difficult to generalise on the effect of initial slope upon equilibrium profiles at the present time, but it seems possible that initial slope does not significantly affect the equilibrium profile when the initial profile is steep and no significant wave energy is dissipated offshore of the breakpoint. Under such conditions the breakers will normally be surging or plunging during the initial stages of profile development. On flat initial slopes where significant energy is dissipated offshore of the breakpoint and/or the breaking waves are spilling, it is possible that no equilibrium can be developed.

4. EXPERIMENTAL INVESTIGATION

The purpose of the present investigation was to compare the equilibrium beach profiles and associated processes produced by different kinds of breaking waves in two beach materials with very different permeabilities. The experimental work was divided into two parts:

(i) the determination of all relevant properties of the beach materials;

(ii) the formation of equilibrium beach profiles in a wave basin for each beach material for various wave heights at a constant wave period.

The two beach materials used in this investigation were:

(i) a fine marine sand, d_{50} = 0.22 mm, typical of the beach sands on the exposed beaches of southern Queensland;

(ii) a coarse crushed coal, d_{50} = 1.55 mm, with a similar relative particle size distribution to the sand.

The sediment properties determined were of two types:

(i) those describing the sediment itself, e.g. specific gravity s size distribution, porosity ε and angle of repose;

(ii) those describing hydraulic characteristics associated with the sediment, e.g. fall velocity w, fluidising velocity w_f and permeability k.

The values of some of these properties are shown on figures 2 and 3 while the complete data is given in a separate report (Gourlay 1980).

The beach profile tests were made in a two dimensional wave basin 14.7 m long, 3.05 m wide, and 0.6 m deep equipped with a suspended paddle type wave generator. In each case the beach material was formed to an initial slope of 1 in 13. The water depth offshore of the beach h_i was 0.368 m. The wave period was 1.9 s for all tests and 8 or 10 tests were made for each material with deepwater wave heights varying from 23 to 183 mm.

Tests were run for sufficient time to reach equilibrium, the test durations varying from 4 to 30 hours. Equilibrium was taken as being reached when the wave uprush limit and breakpoint location did not alter position significantly with tine. Once the profile had reached equilibrium the following quantities were measured:

(i) incident wave heights and reflection coefficient along 10 equally spaced lines offshore of the beach;

(ii) wave height transformation along centre profile, including crest and trough elevations, from offshore through the surf zone to the beach;

(iii) location, height and type of breakers; location of plunge point, if any; location of uprush limit and time of travel of broken wave from breakpoint to uprush limit;

(iv) wave set-down and set-up along centre profile from offshore to landward of uprush limit;

and after the wave generator was turned off:

(v) beach profiles along 10 equally spaced lines over the full extent of the wave formed profile.

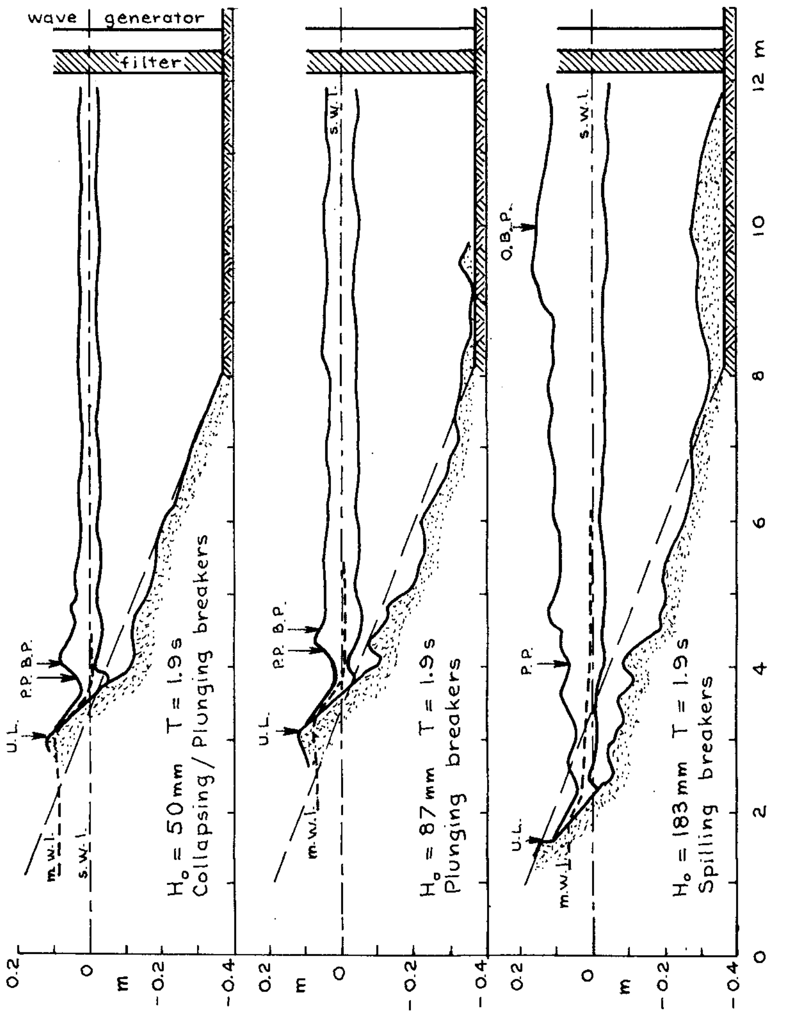
5. EXPERIMENTAL RESULTS

5.1 Beach Profiles and Mean Water Level

The experimental profiles measured along the centre of the wave basin together with wave heights and mean water levels are given for selected tests on figure 2 (sand) and figure 3 (coal). Steep reflective beaches with step type profiles were developed by low waves on both beach materials, while flat dissipative beaches with offshore bars were developed with the highest waves. In both cases the smallest waves produced erosion of the profile offshore of the breakpoint and accretion of the beach in the form of a large berm. Waves of intermediate height produced erosion of the offshore profile with accretion both on the beach and further offshore. Only the highest waves produced erosion of both the beach and inner surf zone and consequent deposition further offshore. The accreting, transition and eroding beaches generally corresponded with the occurrence of surging, plunging and spilling breakers respectively. For both beach materials the offshore profile seaward of the breakpoint was steepest just before the breakers changed from plunging to spilling.

Significant differences in detail were also evident between the profiles formed in the two different beach materials. All the beach profiles formed in sand had an almost constant beach face slope of 12° between the still water line and the berm crest (uprush limit). The sand beach behaved as an almost impermeable surface with both the uprush and the backwash flowing parallel to the beach face. Beach profiles in sand showed a breakpoint bar with plunging breakers. In contrast the beach profiles formed in the coal were much smoother in shape and a bar was not formed with plunging breakers. The most obvious feature of the coal beach profiles formed by low wave heights was the very steep berm which was built up at the uprush limit. With surging breakers this berm was very high and had a very steep face above the mean water level with a slope approaching 55°, the critical angle for stability of this beach material. On the other hand, the slope of the beach face at the still water line was very much less than this value, i.e. of the order of 4° for the higher waves. It is quite evident that the permeability of the coal beach was very important and the mechanism whereby this large berm was built up involved the uprush percolating into the steep berm face, draining vertically downwards through the deposited material, and then emerging as the backwash as the base of the beach below the mean water level.

Offshore of the breakpoint, the mean water level was almost horizontal with comparatively little wave set-down, particularly for the coal beach. Mean water level started to rise at the plunge point and the maximum elevation of mean water level (maximum wave set-up) occurred within the beach landward of the uprush limit. For the spilling breakers occurring with the largest waves, mean water level rose at a very flat slope between the outer and inner breakpoints. The mean water level gradient inshore of the inner breakpoint was significantly steeper than offshore but flatter than that for the lower wave heights.

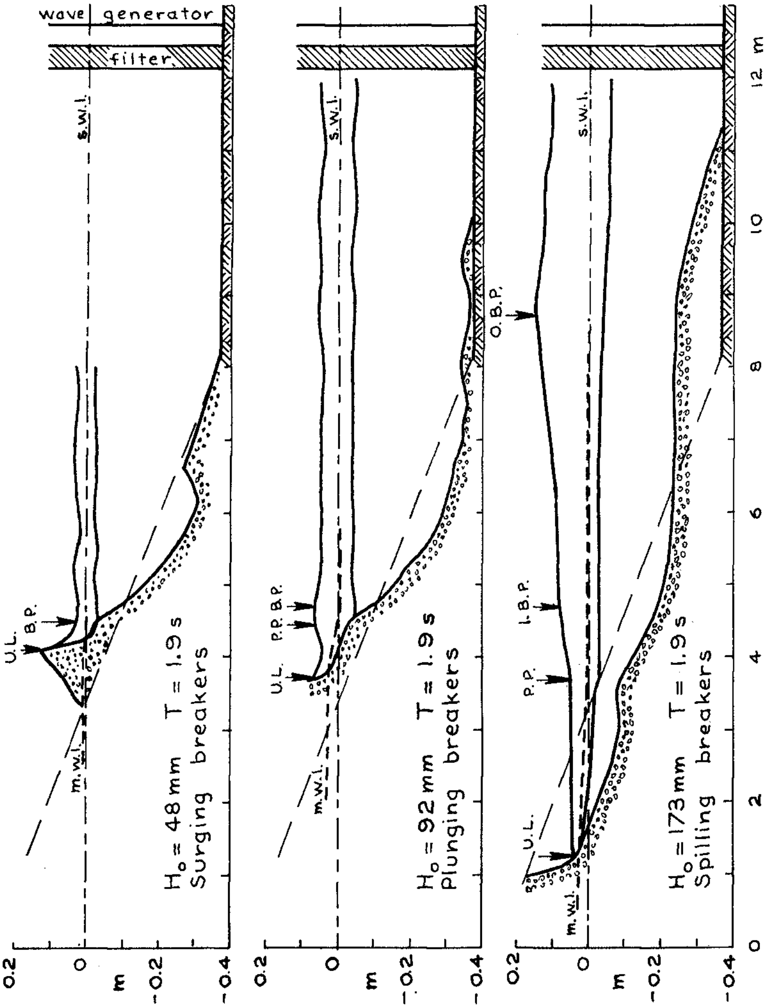


Marine sand

d_{50} = 0.22 mm σ_g = 1.24 s = 2.67

ϵ = 0.415 $w(d_{50})$ = 27 mm/s w_f = 0.41 mm/s

Figure 2



Crushed coal

d_{50} = 1.55 mm σ_g = 1.27 s = 1.34

ϵ = 0.51 $w(d_{50})$ = 46 mm/s w_f = 2.7 mm/s

Figure 3

5.2 Beach and Surf Zone Parameters

The basic experimental data measured just before the end of each test and from the profiles surveyed just afterwards is presented elsewhere (Gourlay 1980). The parameters are breaking wave height H_b, wave reflection r, maximum wave set-up $\bar{\eta}_m$, berm crest/dune foot height z_c, surf zone width x_d, relative uprush time or "phase difference" T_u/T and beach slope at still water line tan α_{swl}. These parameters are plotted as functions of the basic independent variable, deepwater wave height H_o on figure 4.

In virtually all cases the magnitudes of the various parameters are greater for the impermeable sand beach than for the very permeable coal beach. The quantity with the least difference is the breaker height but in most other cases the magnitudes of the coal beach parameters are about half those of the sand beach. In most cases the breaker type is seen to influence the form of the relationship. For instance the maximum berm height occurs when the surging breakers are just changing to collapsing breakers. Both plunging and spilling breakers dissipate more energy offshore of the beach with a consequent reduction in the wave uprush which determines the berm/dune foot height. The maximum wave set-up or wave induced groundwater level behind the beach also varies with breaker type but its maximum value appears to be associated with profile shape rather than breaker type. Both the surf zone width and maximum uprush time are different for each beach material with surging and plunging breakers but tend to similar values with spilling breakers.

As discussed earlier, the dimensionless fall velocity H_o/Tw is an important parameter influencing beach processes and beach profile shape. Its significance is shown on figure 5 where H_b/H_o, $\bar{\eta}_m/H_o$, z_c/H_o, x_d/L_o and T_u/T are all plotted as functions of H_o/Tw or in actuality H_o/w since T is constant for these experiments. The following results are obtained:

(i) The maximum wave set-up occurs at about $H_o/Tw = 1$ for both beach materials.

(ii) $T_u/T = 0.5$ when $H_o/Tw = 1$ and profiles for $H_o/Tw < 1$ are definitely step type profiles. Bar type profiles are not formed until $H_o/Tw \approx 1.4$ to 1.5.

(iii) The relative berm height z_c/H_o has a maximum value for the coal beach when $H_o/Tw < 0.6$.

(iv) Both the relative surf zone width x_d/L_o and the relative uprush time T_u/T are unique functions of H_o/L_o for both materials except for the highest spilling breakers. The shapes of these functions indicate that x_d/L_o is a function of T_u/T as shown by Sunamura and Horikawa (1974).

Since the wave period was not varied in these experiments, any parameter involving T or L_o ($= gT^2/2\pi$) has not yet been justified. A detailed analysis of data from other sources has not yet been made, but

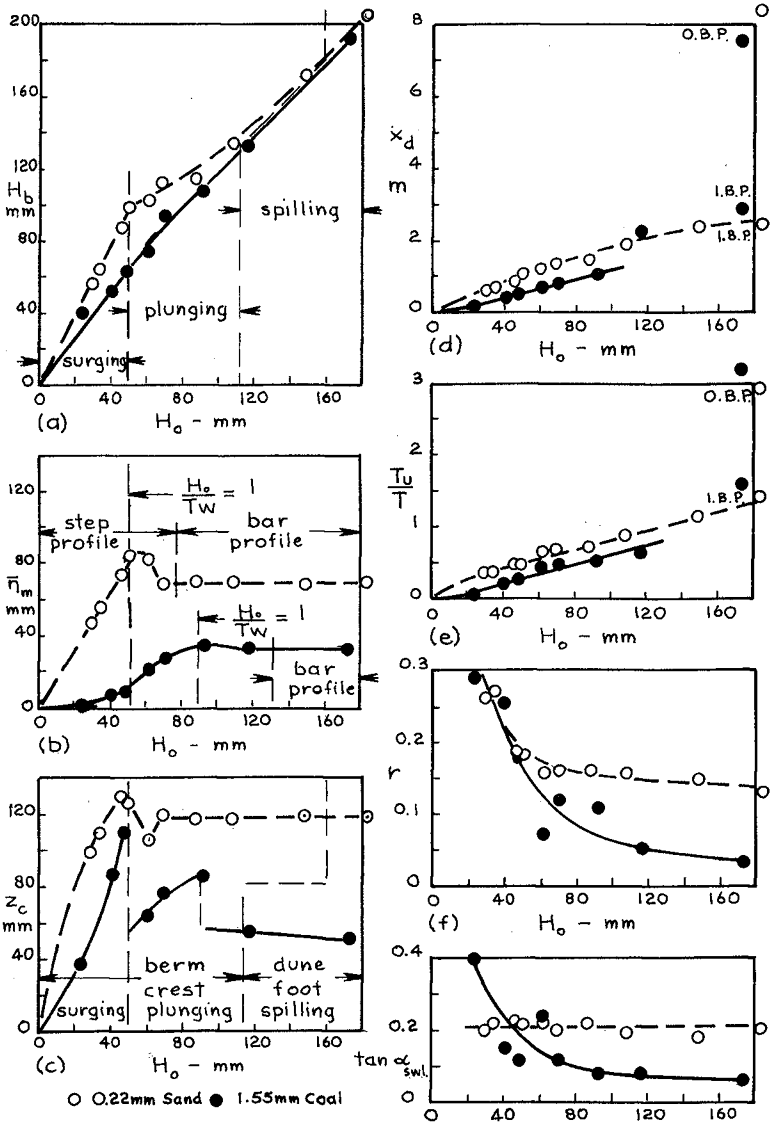

(a)
H_b mm
H_o - mm
surging
plunging
spilling
(b)
$\bar{\eta}_m$ mm
$\frac{H_o}{Tw} = 1$
step profile
bar profile
(c)
z_c mm
surging
berm crest plunging
dune foot spilling
(d)
x_d m
O.B.P.
I.B.P.
(e)
$\frac{T_u}{T}$
(f)
r
(g)
tan α_{swl}
O 0.22mm Sand ● 1.55mm Coal

Figure 4

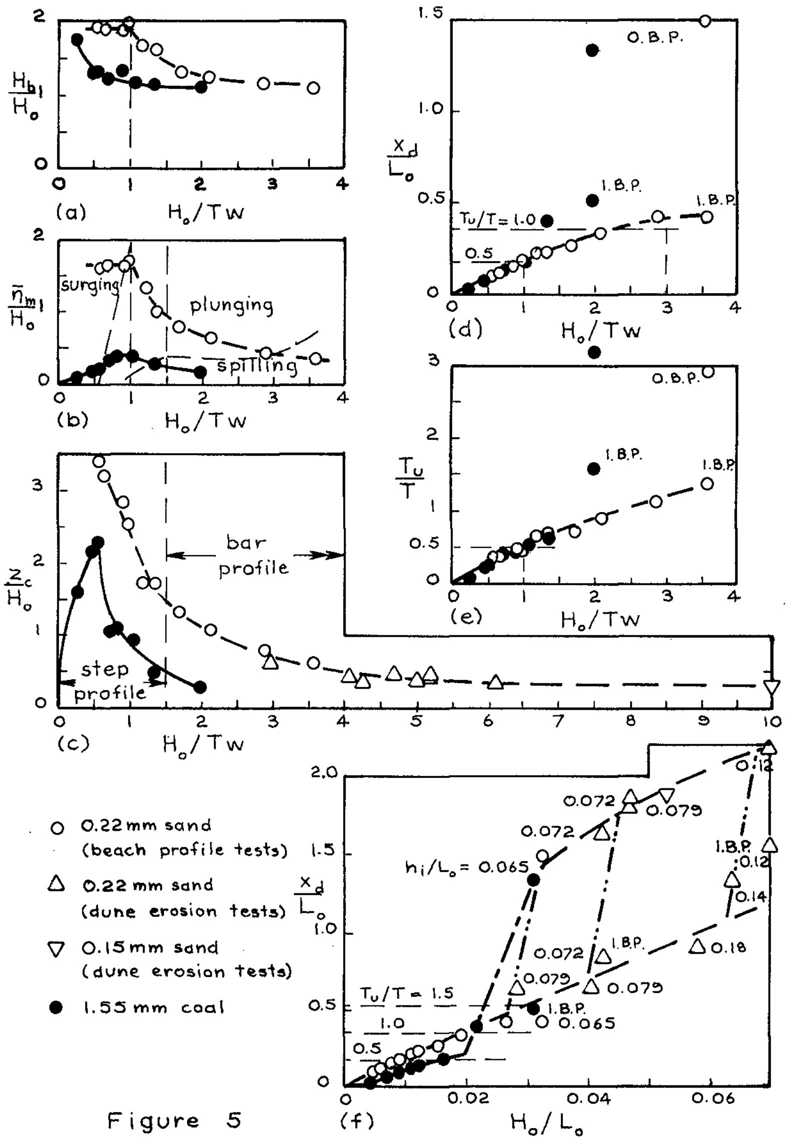

(a)
H_{b1}/H_o
H_o/Tw
(b)
$\bar{\eta}_{m1}/H_o$
surging
plunging
spilling
H_o/Tw
(c)
Z_c/H_o
bar profile
step profile
H_o/Tw
(d)
X_d/L_o
O.B.P.
I.B.P.
$T_u/T = 1.0$
0.5
H_o/Tw
(e)
T_u/T
O.B.P.
I.B.P.
H_o/Tw
(f)
X_d/L_o
$h_i/L_o = 0.065$
0.072
0.079
0.12
0.14
0.18
I.B.P.
$T_u/T = 1.5$
1.0
0.5
H_o/L_o
○ 0.22 mm sand (beach profile tests)
△ 0.22 mm sand (dune erosion tests)
▽ 0.15 mm sand (dune erosion tests)
● 1.55 mm coal

Figure 5

some data from earlier experiments on the erosion of sand dunes (Gourlay 1968, van der Meulen and Gourlay 1968) has been examined. This data is for 0.22 mm sand very similar to that used in the present tests, with one test with 0.15 mm sand. Wave periods varied between 1.04 and 1.63 s while wave heights were such that wave steepness H_o/L_o was generally greater than the largest steepness used in the present tests. The only quantities conveniently available were dune foot height (uprush limit) z_c and surf zone width x_d. As indicated on figure 5c the relationship between z_c/H_o for the dune erosion data and H_o/Tw is quite consistent with that for the present tests.

When x_d/L_o for the dune erosion data was plotted as a function of H_o/Tw (not shown on figure 5d), no clear picture was presented since all the additional data was for $H_o/Tw \gtrsim 3$ which was the region where this parameter tended to separate rather than unify the data from the present tests. On the other hand, it was found if x_d/L_o were plotted against the deepwater wave steepness H_o/L_o then a reasonably consistent pattern emerged (figure 5f). For $H_o/L_o < 0.03$, x_d/L_o is a simple function of H_o/Tw. For $H_o/L_o > 0.03$ there are two possible surf zone widths. The narrower surf zone (small x_d/L_o) is an extension of the low wave steepness sand curve. It also includes surf zone widths inshore of the inner breakpoint on wide surf zones. Wide surf zones (large x_d/L_o) occur when significant deposition occurs on the level bottom of the wave basin seaward of the initial sand slope in the present tests or on a horizontal section of the offshore profile seaward of an approximately 1 in 10 slope in the dune erosion tests. Thus there appears to be an effect of initial profile shape present in the form of different values of h_i/L_o where h_i is the depth offshore of the initial plane beach or the depth of the horizontal section of the initial profile in the dune erosion tests. As indicated on figure 5f the critical steepness of 0.03 for the initiation of a wide surf zone in these tests corresponds to $h_i/L_o = 0.065$. About half the dune erosion tests have values of $h_i/L_o = 0.072$ or 0.079 and those with $H_o/L_o > 0.04$ have relatively wide surf zones. On the other hand, tests with h_i/L_o = 0.14 and 0.18 lie on the narrow surf zone line with the former possibly on the point of transition to a wide surf zone at $H_o/L_o \simeq 0.06$. Certainly a test with $h_i/L_o = 0.12$ and $H_o/L_o > 0.06$ has a wide surf zone.

It appears from the preceding that the intiial profile shape as typified by the ratio h_i/L_o in these tests does affect the shape and particularly the surf zone width of the equilibrium profile when waves reach a certain critical steepness, the value of which increases with the magnitude of h_i/L_o. This effect is possibly a consequence of significant energy dissipation occurring offshore of the original breakpoint during early stages of tests with relatively steep large waves. As suggested earlier, such an effect could be expected to occur on flat plane beaches, but not on steep ones. Hence the above results tend to confirm the idea that the initial profile shape affects the shape of the equilibrium profile when the former is flat but not when it is steep.

5.3 Beach Permeability

While it is evident that the parameter H_o/Tw is of considerable significance in representing the beach profile data particularly for x_d/L_o and T_u/T when the latter parameter is less than 1.0, it is also evident from figure 5 that there are significant differences between the impermeable sand beach and the permeable coal beach with regard to other beach and surf zone parameters. These effects are almost certainly related to the differences in permeability of the two beach materials. In fact the magnitudes of these differences are in most cases directly related to the ratio between the fluidising velocity w_f and the fall velocity w as can be seen in figure 6 where w_f/w has been introduced as a multiplier to the various dependent variable parameters z_c/H_o, $\bar{\eta}_m/H_o$, etc. With the exception of figure 6a for H_b/H_o, where the independent variable parameter H_o/Tw has been multiplied by w_f/w, all the other figures show that when the dependent variable is multiplied by w_f/w, the data points for both sand and coal beaches lie on the same curve when $H_o/Tw > 1$. Moreover there is a tendency for the modified parameters to become constant when $H_o/Tw > 3$.

The data plotted on figure 6 shows that there is no qualitative difference in behaviour between the two beach materials when $H_o/Tw > 1$, only a quantitative one. On the other hand, when $H_o/Tw < 1$ there are significant differences in the nature of the hydraulic processes within the surf zone, which is in fact confined to the uprush-backwash cycle, between the impermeable sand beach and the very permeable coal beach. The nature of these differences has been already indicated in the discussion on beach profiles. For the sand beach the hydraulic parameters involving H_b and $\bar{\eta}_m$ are independent of H_o/Tw when the latter is less than 1.0 while the beach slope is essentially constant for all values of H_o/Tw. Both the modified wave reflection coefficient $r\ w_f/w$ and the modified surf zone similarity parameter $[(\tan \alpha_{swl})/\sqrt{H_o/L_o}\ ]w_f/w$ appear to follow similar trends with H_o/Tw. Unfortunately the scatter of the data is too much to compare the relationship between these two parameters with that for a fixed plane beach.

The exact significance of the above results and particularly the ratio w_f/w has not yet been worked out in theoretical terms, but it seems quite certain that w_f is a very important sediment property which determines the shape of beach profiles formed in relatively large light weight sediments. w_f has been described as the fluidising velocity, that is it is the overall upward velocity of flow through a bed of sediment which just causes that sediment to be fluidised or to become unstable. It is related to the permeability k by the relationship

$$w_f = k\ i_c$$

where $i_c = (s-1)(1-\varepsilon)$ is the critical hydraulic gradient at fluidization. On the other hand, w_f may be interpreted as the fall velocity of the sediment at maximum concentration of sediment particles. Under such conditions particle interference is a maximum and the fall velocity is very much less than that for widely separated particles in still water.

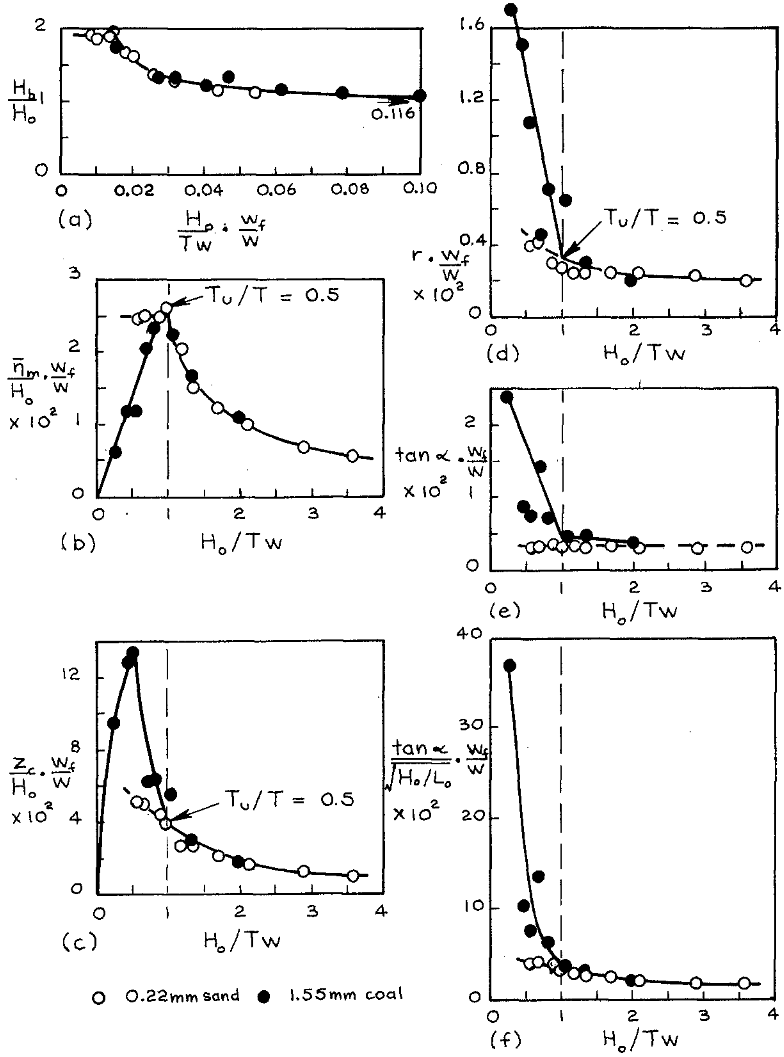

(a)
(b)
(c)
(d)
(e)
(f)
H_b/H_o
$\frac{H_o}{Tw} \cdot \frac{w_f}{W}$
0.116
$\frac{\bar{\eta}_m}{H_o} \cdot \frac{w_f}{W} \times 10^2$
$\frac{Z_c}{H_o} \cdot \frac{w_f}{W} \times 10^2$
$r \cdot \frac{w_f}{W} \times 10^2$
$\tan\alpha \cdot \frac{w_f}{W} \times 10^2$
$\frac{\tan\alpha}{\sqrt{H_o/L_o}} \cdot \frac{w_f}{W} \times 10^2$
H_o/Tw
$T_u/T = 0.5$
○ 0.22mm sand ● 1.55mm coal

Figure 6

For spherical particles w_f/w is a constant for both very small and large particles, the magnitude of this ratio being a function of the dimensionless particle size $g^{1/3}(s-1)^{1/3}d/\nu^{2/3}$ and the porosity ε of the deposited sediment. This ratio w_f/w is smaller for small particles than large ones since the permeability and hence w_f of sediments decreases both as the porosity decreases and as the specific surface (surface exposed to fluid per unit volume of solid) increases.

6. SUMMARY AND CONCLUSIONS

(i) The dimensionless fall velocity H_o/Tw, which represents the behaviour of the sediment particles stirred up by the breaking waves in the surf zone, is an important parameter influencing surf zone hydraulics and the form of the equilibrium beach profile inshore of the breakpoint. In particular the wave set-up has a maximum value when $H_o/Tw = 1$ and both the relative surf zone width x_d/L_o and relative uprush time T_u/T are unique functions of H_o/Tw when $T_u/T < 1$.

(ii) While H_o/Tw is a necessary and probably sufficient parameter for defining similarity conditions for model beaches formed in relatively impermeable sand, it is not sufficient for defining similarity conditions for model beaches formed in relatively permeable materials, particularly lightweight materials such as crushed coal. For permeable beaches the ratio w_f/w, which is the ratio of the maximum possible flow velocity within the deposited sediment to the maximum particle velocity in still water, is also important.

(iii) Similarity of the beach profile with respect to the beach face and its associated hydraulics is determined by both H_o/Tw and w_f/w as follows:

$H_o/Tw < 1$ - Hydraulic conditions within the beach face are significantly different for impermeable and permeable beach materials and no similarity is possible.

$1 < H_o/Tw < 3$ - Both H_o/Tw and w_f/w determine the similarity of the beach face.

$H_o/Tw > 3$ - Beach face parameters become independent of H_o/Tw and w_f/w is sufficient for similarity.

(iv) The shape of the initial profile does not appear to affect the shape of the equilibrium profile when the former is steep and offshore accretion is confined to the initial plane profile surface. If the initial slope is flat and/or offshore accretion occurs on the horizontal bottom of the wave basin or on an offshore horizontal section of the initial profile then either a wide or a narrow surf zone is possible. The occurrence of a wide surf zone depends upon the magnitude of both H_o/L_o and h_i/L_o.

(v) The results presented in this paper concerning the importance of w_f/w need to be extended with further experimental data for other beach materials including a permeable very coarse sand/fine gravel and a finer crushed coal. Further tests at various wave periods and initial profile slopes/shapes are also required to define the limits of the influence of H_o/Tw upon surf zone hydraulics and equilibrium beach profiles.

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