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Application of a Non-Linear Shallow Water Theory to Swash Following Bore Collapse on a Sandy Beach

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ABSTRACT

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The non-linear shallow water theory is believed to be capable of describing many features of wave behaviour in the coastal zone. A set of solutions to the governing equations exists for swash following bore collapse on a hydraulically smooth and impermeable beach. These solutions predict that the maximum swash height is proportional to the square of the initial shoreline velocity, the locus of shoreline position through time is parabolic, the maximum swash depth at any position on the beach is a quadratic function of its distance from the initial shoreline position, the maximum swash depth at any position on the beach occurs before the time of maximum uprush, and a retrogressive bore forms in the backwash.

All of these predictions have been observed in field data collected from a number of sandy beaches in southeast Australia. However, the theory consistently over-predicted the magnitude of the parameters measured. Evidence is presented to suggest that this discrepancy is due to the effects of friction and infiltration acting on the swash lens, which are not initially accounted for in the theory. If the available evidence is accepted, then the combined effects of friction and infiltration on a sandy beach serve to reduce the maximum swash height to approximately 65% of that expected from theory.

Aside from the theoretical over-prediction of the magnitude of the swash parameters measured, the gross flow behaviour of the uprush on a rough and permeable beach face appears to be successfully described by the inviscid theory. There is some promise, therefore, for successfully modelling the effects of friction and infiltration within the framework provided by the theory. Unfortunately the backwash stage of the swash cycle is not so well predicted. It seems that a better understanding of both the backwash bore and the behaviour of granular-fluid flows is required before the backwash is successfully modelled.

ADDITIONAL INDEX WORDS: *Uprush, backwash, swash height, shoreline displacement, swash lens geometry, friction, infiltration.*

INTRODUCTION

The action of waves on the beach face, termed swash, provides the principal mechanism for sediment exchange between the subaqueous and subaerial zones of the beach system. A complete understanding of the morphological behaviour of beach systems requires detailed investigations of the swash zone, particularly in relation to the interaction between fluid and sediment. The study reported here contributes to this field of investigation by examining the capacity of the non-linear shallow water theory to describe wave behaviour in the swash zone of natural beaches.

Water motion in the swash zone is generally caused by a quasi-steady super-elevation of the water surface above the still water level, which is known as set-up, and wave driven oscillations about this set-up level, which are known as swash (GUZA and THORNTON, 1982). Swash oscillations occur over a range of frequencies, but can generally be grouped into three categories according to the most energetic wave frequency operating in the inner surf zone. The first category are infragravity waves, which have periods typically between 30 and 300 sec (HOLMAN, 1981). The second category are the higher frequency, sub-harmonic edge waves which have periods twice that of the incident waves; typically 15 to 25 sec (WRIGHT, 1982). The third category of swash oscillations are directly associated with the uprush and backwash of incident waves, and have periods typically between 5 and 15 sec (BRADSHAW, 1980).

This study specifically addresses swash produced by incident waves breaking on sandy beaches. Water surface elevation and velocity spectra measured in the inner surf zone and swash

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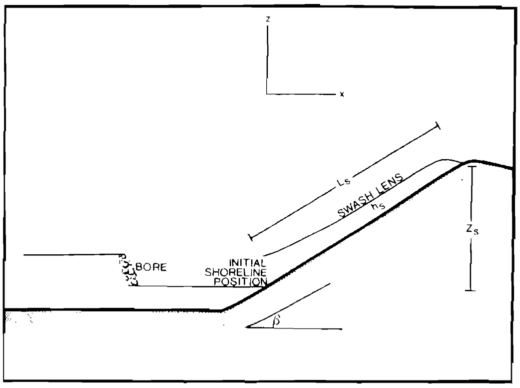

Figure 1. Definition of terms that relate to the swash cycle.

zone on a wide range of beaches have shown that significant amounts of energy exist at incident wave frequencies near the shoreline (BRADSHAW, 1980; WRIGHT and SHORT, 1984; WRIGHT *et al.*, 1986). More specifically, these researchers have demonstrated that incident waves are important in the inner surf zone and swash zone on Wright and Short's reflective and intermediate beach states; namely the 'low tide terrace', 'transverse bar and rip', 'rhythmic bar and beach' and 'longshore bar and trough' states. Their 'dissipative' beach state is not considered here, due to the nearly complete dissipation of incident wave energy near the shoreline on these beaches.

Cursory observations of incident waves on reflective and intermediate beaches indicate that the swash oscillations frequently span the entire beach face (*i.e.* beach step to berm crest). This suggests that they must play a significant role in shaping the morphology in this zone, particularly during slight to moderate energy conditions when infragravity waves in the surf zone are least important. Observations of incident bores propagating across the surf zone and beach face on an infragravity wave crest, to cause substantial foredune scarping during storms (WRIGHT, 1980), suggest that incident swash may still be important even under high energy conditions when infragravity waves are dominating the surf zone energy spectrum.

For the specific purposes of this study, the swash cycle is defined to begin when a surf zone bore arrives and collapses at the initial shoreline position, at which time the shoreline is set in motion and becomes the leading edge of the swash lens (Figure 1). The uprush stage of the swash cycle is complete when the moving shoreline (or leading edge of the swash lens) has climbed to its point of maximum landward displacement. Following the uprush stage, the shoreline begins to return seaward, thus initiating the backwash stage. This stage is completed when the shoreline returns to its initial position. The initial shoreline position for the swash cycle migrates back and forth across the beach face with the passage of infragravity waves and the tide. The period of this migration is typically at least an order of magnitude larger than the incident swash cycle, thus the initial shoreline position for a single swash period can be considered stationary.

Significant advances have been made to date in applying the non-linear shallow water theory to the study of swash. By proving a set of lemmas and corollaries, HO and MEYER (1962) and SHEN and MEYER (1963) used the theory to obtain solutions for bore propagation, shoreline displacement, shoreline velocity, swash height and geometry of the swash lens. Subsequent studies have examined the implications of this analytical work using numerical techniques (*e.g.* FREEMAN and LEMEHAUTE, 1964; AMEIN, 1966), and experimental techniques in both the laboratory (*e.g.* KISHI and SAEKI, 1966; MILLER, 1968) and to a limited extent in the field (WADDELL, 1973; BRADSHAW, 1982).

In order to expand the limited field application of the theory the aim here is to quantitatively compare the non-linear shallow water theory's predictions for swash following bore collapse against field data collected on a number of natural, sandy beaches.

THEORETICAL BACKGROUND

The Non-Linear Shallow Water Equations

The first-order, non-linear shallow water equations (SWE) are deemed suitable for modelling two dimensional water motion in the vicinity of the beach (STOKER, 1957; PEREGRINE, 1972). The depth integrated equations describing conservation of mass and momentum are

$$\frac{\partial[u(\eta + h)]}{\partial x} + \frac{\partial \eta}{\partial t} = 0 \tag{1}$$

and

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \eta}{\partial x} = 0 \tag{2}$$

(STOKER, 1957), where u is the horizontal water velocity, η is the water surface elevation relative to the still water level, h is the still water depth, x is the horizontal distance in the direction of wave propagation, t is the time and g is the gravitational acceleration constant. The SWE assume that: (1) The water surface slope is not much larger than the beach slope (*i.e.* the wave is long), (2) the water pressure is hydrostatic, (3) the vertical distribution of horizontal water velocity is uniform, and (4) the fluid is inviscid, incompressible and irrotational.

Progressive waves that can be described by the SWE steepen as they shoal towards the beach (GREENSPAN, 1958; COWELL, 1982). The concomitant change in water particle acceleration and surface slope thus leads to a violation of the first three assumptions of the theory. Analysis of the wave motion beyond the point where the water surface slope becomes too steep requires the *ad hoc* inclusion of some theory to describe the propagation of the wave crest while the SWE are applied outside the wave crest region. The traditional approach used in the literature to date is to adopt bore theory.

Bores in the Inner Surf Zone

Bores form in the inner surf zone of WRIGHT and SHORT's (1984) intermediate type beaches, following a wave transformation stage, from either a non-saturated breaker or a plunging breaker (COWELL, 1982). On these beaches bores provide the initial impetus for the swash cycle. PEREGRINE (1966) classified bores as either undular or fully developed, depending on the ratio of bore height to water depth upstream of the bore. The discussion is restricted here to fully developed bores as these were the only type present during the experiments. A fully developed bore occurs when the bore height to water depth ratio is greater than 0.75. It is generally recognized by its step-shaped profile and intense turbulence on the shoreward face.

In the case of a fully developed turbulent bore propagating over a sloping beach, laboratory experiments indicate that as a first approximation, deviations from hydrostatic pressure and the effects of bed friction are negligible (SVENDSEN and MADSEN, 1984; SVENDSEN, 1987). The velocity of the bore front, U_b, can therefore be written as

$$U_b = \sqrt{\frac{gh_1(h_0 + h_1)}{2h_0}} \tag{3}$$

and the water velocity, u_b, as

$$u_b = \frac{U_b(h_1 - h_0)}{h_1} \tag{4}$$

(STOKER, 1957), where h_0 and h_1 are the water depths on the low and high side of the bore respectively. These equations assume that the water on the low side of the bore is stationary. KISHI and SAEKI (1966) provided corrections for (3) and (4) for the situation of a weak opposing flow on the low side of the bore, which could model the common situation of bores propagating shorewards in the presence of a seaward directed flow such as undertow.

Since $h_0 \rightarrow 0$ as the shoreline is approached, (3) and (4) imply that U_b and u_b tend to infinity. However, for the wave to remain a bore, U_b can never exceed the value of $[u_b + \sqrt{(gh_1)}]$ immediately behind the bore front. This arises from the fact that the bore derives its energy from the wave elements behind and can therefore never exceed their speed (FREEMAN and LEMEHAUTE, 1964). It follows then, that $u_b \rightarrow U_b$ as $h_0 \rightarrow 0$, and upon arrival at the beach ($h_0 = 0$) the bore sets the shoreline in motion with an initial velocity $u_0 = u_b = U_b$. WHITHAM (1958) further demonstrated this behaviour by beginning with (3) and (4) and deriving an ordinary differential equation, which could be solved to yield the evolution of bore height and velocity as the bore approached the shoreline. The accuracy of this equation was subsequently confirmed by directly solving (1) and (2) for the same problem (KELLER *et al.*, 1960). These early theoretical studies showed that the terminal bore velocity and hence the initial swash velocity, u_0, is finite and can be calculated within the context of the non-linear shallow water theory.

Swash on a Smooth and Impermeable Beach

The rapid decrease in bore height at the initial shoreline position predicted by WHITHAM (1958) and KELLER *et al.* (1960) indicates both bore collapse and a singularity of water acceleration in the SWE. The advancement of the non-linear shallow water theory to describe swash was only possible after this singularity was re-interpreted both physically and mathematically (SHEN and MEYER, 1963; MEYER and TAYLOR, 1972). It is physically interpreted as a change in wave form from that of a shock wave to a rarefaction wave, where the initial shoreline becomes the leading edge of the latter (FREEMAN and LEMEHAUTE, 1964). The mathematical re-interpretation of the shore-singularity allows the moving shoreline or leading edge of the rarefaction wave (swash lens) to be modelled on the basis of several simple corollaries of the SWE.

Ho *et al.*'s (1963) interpretation of the corollaries contained in SHEN and MEYER's (1963) original analysis of the SWE provides a useful physical description of the swash lens on a smooth and impermeable beach. In their model the swash lens is assumed to be divisible into small 'fluid elements', each containing the same mass of water at all times. The motion of each element depends only on the pressure exerted by the adjacent elements and gravity. In the inviscid case the leading 'fluid element' is always moving faster than the elements behind, since the swash is a rarefaction wave (STOKER, 1957; FREEMAN and LEMEHAUTE, 1964). Thus the pressure acting on this front element is negligible. Once the shoreline has been accelerated by bore collapse to its maximum velocity u_0, its motion can then be studied by simply considering the balance of forces acting on a single 'fluid element' climbing the beach.

Consider the situation shown in Figure 1 where a bore propagating shorewards arrives at the initial shoreline position x = 0 at time t = 0. Assumptions relating to the nature of the fluid are the same as those listed with the SWE. It is further assumed that the wave period is sufficiently long to ensure no backwash interaction occurs and that the beach face is hydraulically smooth and impermeable. The equation of motion for the leading edge of the swash lens or moving shoreline can be written as

$$m\frac{d^2X_s}{dt^2} + mg(\sin\beta) = 0 \qquad (5)$$

where m is the mass of the leading fluid element, X_s is its position relative to the initial shoreline position and β is the beach face slope. Through integration and adopting the initial condition that $dX_s/dt = u_0$ when t = 0 the shoreline velocity, U_s, is obtained;

$$\frac{dX_s}{dt} = U_s(t) = u_0 - gt(\sin\beta) \qquad (6)$$

Furthermore, since the shoreline displacement is zero when t = 0, integration of (6) yields the time-history of the shoreline position;

$$X_s(t) = u_0t - 0.5gt^2(\sin\beta) \qquad (7)$$

When $U_s = 0$ the shoreline is at its maximum landward displacement. From (6) this occurs when

$$t = t_{(max)} = \frac{u_0}{g(\sin\beta)} \qquad (8)$$

Substituting (8) into (7) yields the maximum swash length

$$L_s = \frac{u_0^2}{2g(\sin\beta)} \qquad (9)$$

Using trigonometry the maximum swash height, Z_s, can also be obtained;

$$Z_s = \frac{u_0^2}{2g} \qquad (10)$$

SHEN and MEYER (1963) provided an approximation for the swash depth, h_s, which can be written as

$$h_s(x, t) \approx \frac{(X_s - x)^2}{(3t)^2} \qquad \text{as } (X_s - x) \to 0 \qquad (11)$$

The water surface elevation in the swash zone (relative to the initial shoreline position), η_s, is therefore

$$\eta_s(x, t) \approx h_s + x(\tan\beta) \qquad (12)$$

The maximum swash depth, $h_{s(max)}$, can be obtained by solving $dh_s/dt = 0$ for the condition that $d^2h_s/dt^2 < 0$. From (11)

$$\frac{dh_s}{dt} = \left[\frac{2(X_s - x)}{3t}\right]\left[\frac{x - 0.5gt^2(\sin\beta)}{3t^2}\right] = 0 \qquad (13)$$

It can be shown that the relevant solution (the right square bracket) gives the time that the maximum swash depth occurs as

$$t_m = \sqrt{\frac{2x}{g(\sin\beta)}} \qquad (14)$$

Substitution of (14) into (11) yields

$$h_{s(max)}(x) = \frac{g(\sin\beta)(u_0t_m - 2x)^2}{18x} \qquad (15)$$

These equations describing the swash behaviour are theoretically valid until a singularity of water acceleration occurs during the backwash. The movement of this singularity in the (x, t) plane is graphically represented by a 'limit line', which has been interpreted to indicate the formation and propagation of a landward facing or retrogressive bore (SHEN and MEYER, 1963). Although the origin and motion of the bore cannot be precisely determined from the theory, it is believed to originate up the beach and move seawards within the backwash flow (Ho *et al.*, 1963). At the time that bore inception occurs, the shoreline becomes influenced by flow processes in the interior of the swash lens, and can therefore no longer be described by (5).

HIBBERD and PEREGRINE (1979) used a finite-difference scheme to solve (1) and (2) and model the uprush and backwash of a bore climbing a beach. A retrogressive bore appeared in their backwash calculations, which supports Shen and Meyer's earlier analytical study of the SWE. The effect of the backwash bore observed in Hibberd and Peregrine's model was to cause an increase in both the backwash depth and duration over that expected from (11) (HUGHES, 1989).

The theoretical predictions just presented were compared with field data collected from sandy beaches displaying a range of environmental conditions, in order to determine the capacity of the non-linear shallow water theory for modelling natural swash.

FIELD SITES AND METHODOLOGY

Field Sites

The field sites chosen for this study were restricted to the northern beaches of Sydney, Australia. These beaches are moderately to deeply embayed, typically display surf zone morphologies ranging from the reflective to high energy intermediate beach states of WRIGHT and SHORT (1984), are composed of sediment sizes ranging from fine to coarse sand, and experience a moderate to high energy swell wave climate. A more complete description of their geomorphology and the regional wave conditions can be found in WRIGHT (1976) and SHORT and WRIGHT (1981).

In order to test the equations describing swash behaviour, certain experimental conditions are required to accommodate the assumptions of the theory. Incident wave periods need to be sufficiently large to avoid interference of the uprush with the preceding backwash, levels of wave refraction need to be sufficient to ensure that wave rays near the shoreline are normal to the beach, and the beach face needs to be sufficiently planar in the longshore direction to ensure that the swash flow is two-dimensional. The wide range of periods associated with natural waves and the secondary refraction of waves over surf zone morphology frequently confounds this description. However, the environmental characteristics of the beaches in the Sydney region ensured that the chosen field sites satisfied these constraints for periods sufficient to obtain the necessary data. The range of beach slopes and grain sizes studied were 0.093–0.15 and 0.31–2.00 mm respectively. In this study the beach slope was measured to represent the active swash zone; typically between the berm crest and top of the beach step.

Field Experiments

An experimental design fashioned around the swash capacitance probes described by WADDELL (1973) was used to collect the required field data. The probe consists of a vertical wire supported by a frame which is inserted into the beach. The water and wire of the probe act as the two plates of a capacitor and the teflon insulation of the wire acts as the dialectric. The output capacitance of the probe, which is converted to a DC voltage through the associated circuitry, is linearly proportional to the immersed length of the probe. The elevation of the beach surface on the probe is readily determined from the ambient capacitance level present between swash cycles.

Two types of experiments were conducted during the field program.

Type One Experiment

In a Type One Experiment a shore-normal line of range poles marked in 10 cm increments were placed in the inner surf zone. In addition, six swash probes were placed in a shore-normal line across the beach face at a suitable spacing to provide good coverage of the prevailing swash length (Figure 2). The positions of the range poles and swash probes were surveyed together with the beach profile prior to the experiment.

As a bore propagated towards the beach face its progress past the range poles was filmed to provide a measurement of its height and velocity immediately seaward of the swash zone. Filming continued during bore collapse and the early stages of the uprush. This provided a visual record of the bore collapse process and an estimate of the initial swash velocity. The swash probes were activated just before bore collapse occurred to record the progress of the swash lens across the beach using strip chart recorders. When the point of maximum uprush was reached the time was recorded on the chart and the shoreline position on the beach was marked. After the swash lens receded the distance from SP#1 to the point of

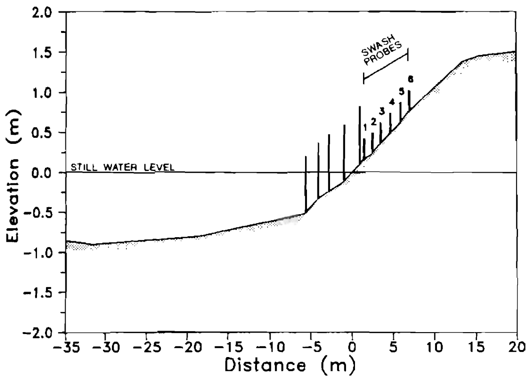

Figure 2. A typical experimental beach profile showing the location of instruments used to measure swash parameters in a "Type One Experiment."

maximum uprush was measured by an observer with a tape. Data recording from the swash probes continued until the end of the backwash.

Following each experiment sediment samples were collected from the base of the beach, the mid swash and the limit of maximum uprush. Also, each swash probe was calibrated to determine the coefficients required to convert their voltage output to the immersed length of the probe. The procedure involved raising and lowering the probes by known increments into a container of water and recording the corresponding voltage. The relationship between voltage and immersed length was consistently linear, thus a least squares regression analysis was used to obtain the calibration coefficients.

The point of bore collapse provides a theoretically convenient reference point to define the beginning of the swash cycle. However, the natural variability in both the location and width of the bore collapse zone makes it difficult to use in practice. It was therefore decided to use the swash probe situated furthest seaward as the reference point for the swash parameters measured in this study; namely SP#1 (Figure 2). The initial swash velocity is thus taken as the shoreline velocity recorded at SP#1, the time $t = 0$ is the recorded time of arrival of the shoreline at SP#1, and both the maximum swash length and swash height are measured relative to the surveyed position of SP#1. Inspection of the equations in the previous section indicates that this approach causes no limitations, since the equations describe the behaviour of the swash lens relative to any choice of reference point on the beach face, provided that the shoreline velocity is known at the chosen point.

The initial swash velocity was calculated from the number of frames in the film record required for the leading edge of the swash lens to travel the last 0.5 m before reaching SP#1. The maximum percentage error in calculating the velocity in this way is estimated to be $3.75u_0$ (u_0 is in m sec^{-1}) for the range of velocities recorded. Thus the possible error was less than 15% for most of the data, but did reach up to 30% for the larger velocities recorded.

The time of arrival of the shoreline at each probe is clearly recognised as a sharp increase in capacitance over the ambient capacitance of the wetted beach surface between swash cycles. These arrival times were combined with the surveyed positions of the swash probes to obtain the locus of shoreline position through time during the uprush. The experimental error associated with these data is expected to be negligible, due to the rapid response time of the probe's electronics. Unfortunately, the shoreline position during the backwash could not be confidently determined from the capacitance records, because the thinning swash lens mostly had no well defined landward boundary.

The maximum swash height was calculated trigonometrically using the maximum swash length and the measured beach slope. Since the swash length was measured by an observer with a tape its accuracy is not limited by the density of the probes. The experimental error associated with these data is limited to errors in surveying the beach slope, and are therefore expected to be negligible.

The time-history of the swash depth and the maximum swash depth were obtained by calculating the difference between the varying capacitance measured by the probe when it was immersed by the swash lens and the constant, ambient capacitance of the wetted beach face measured between swash cycles. The results were converted to swash depths using the calibration coefficients. Two sources of experimental error are associated with these data. The first arises from the measuring wire interfering with the flow. This was observed to be most problematic near the base of the beach where the largest water velocities occur. The disturbance of the water level occasionally reached 2 cm for the stronger flows, but was usually closer to 1 cm. For typical swash depths on the lower beach face, this is likely to produce an error of approximately 10% of the swash depth. The second possible source of error was caused by the presence of foam floating on the surface of the swash lens. This foam often maintained its thickness for the entire swash cycle. The effect on the measured capacitance may lead to only minor over-estimation of the water depth on the lower beach since depths are relatively large. However, on the upper beach where the foam thickness may be as large as the water depth the effect is more pronounced. When substantial amounts of foam were present it occurred in patches, which appear as oscillations in the records of water surface elevation. This enabled some estimation of the foam's thickness. In considering both possible sources of error it is believed that for the most part, any errors in estimating the swash depth are unlikely to exceed 50% and are most likely to be approximately 15%.

The water surface profile of the swash lens at the time of maximum uprush was calculated by combining the measured swash depth recorded by the probes and the surveyed positions of the probes. The possible sources and magnitude of error associated with these data are the same as those just described.

Type Two Experiment

In a Type Two Experiment the six swash probes were juxtaposed along a shore-normal transect located approximately half way between the base of the beach and the limit of maximum uprush. The measuring wire of each probe was separated from the next by 2.5 cm. The remainder of the experimental procedure was identical to that described for the Type One Experiment. This arrangement provided detailed measurements of the water surface profile of the leading 12.5 cm of the swash lens. Due to the irregularity of wave heights at the shoreline and the stationarity of the probes, measurements were obtained at various positions in the uprush.

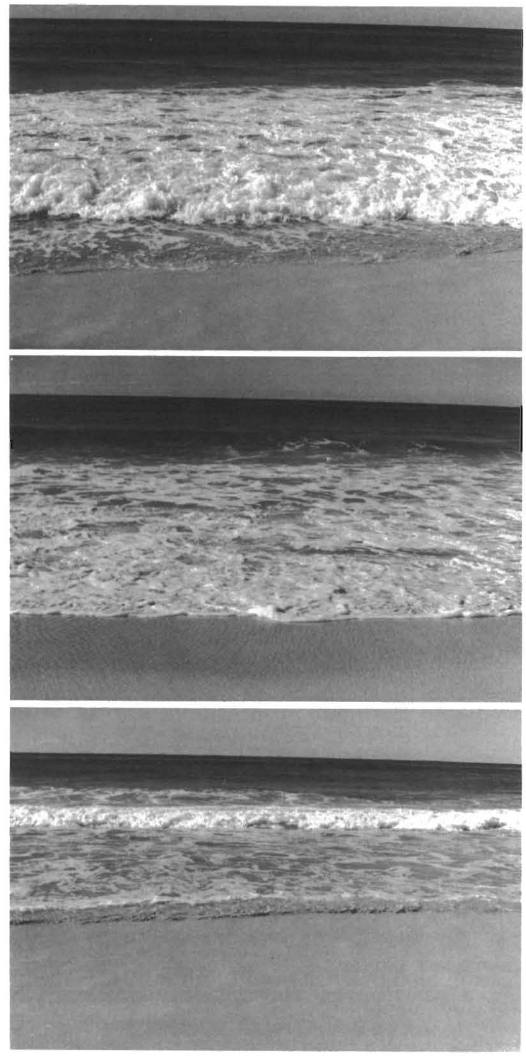

Figure 3. (A), top. Fully developed bore approaching the initial shoreline position. The bore height is approximately 35 cm. (B), middle. Water surface of the swash lens shown during the uprush stage of the swash cycle. (C), bottom. Beach face shown near the end of the backwash stage of the swash cycle.

RESULTS

Bore Collapse at the Shoreline

Examination of the film records indicated that the behaviour of swash following bore collapse on a natural beach appears to compare well with theoretical expectations. The main features of the swash cycle are evident in the series of photographs shown in Figure 3, which are indicative of the experimental conditions observed during this study. In Figure 3A a fully developed bore is shown propagating across a zone of still water towards the shoreline. The typically abrupt changes in water surface elevation and turbulence across the relatively narrow, steep bore front are clearly recognised, as are the relatively small water surface slopes either side of the bore region. When the bore crosses the initial shoreline it collapses and

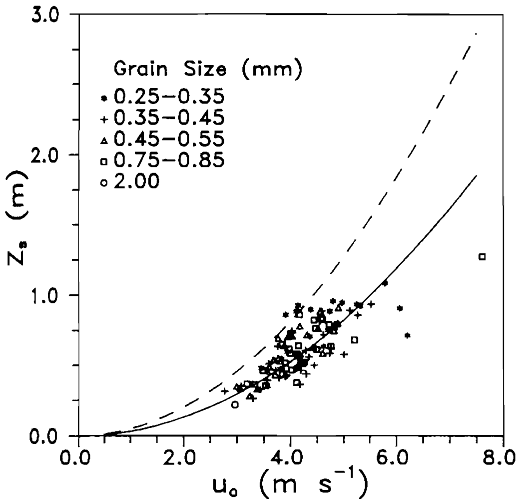

Figure 4. Plot of field data showing the maximum swash height as a function of the initial shoreline velocity and grain size. The dashed and solid lines show respectively the theoretical relationship (10) and the regression model (16).

the free-surface turbulence disappears. The wave then no longer behaves as a bore, but as a rarefaction wave that climbs the beach. The rarefaction wave appears as a relatively smooth lens of water, the depth of which decreases with time and distance travelled (Figure 3B). The foam on the surface of the swash lens is antecedent to the swash phase; it is not generated during the swash cycle. Once the swash lens has reached its maximum height it begins to move down the beach as backwash. The end of the swash cycle is shown in Figure 3C, where the moving shoreline has returned to its initial position and another bore is seen propagating shorewards.

Visually, bore collapse is considered to be complete when there is no longer any water upstream of the bore front and turbulence generation at the free surface ceases. These conditions correspond to the time when the wave front can no longer be theoretically described by a bore. Upon arrival at the initial shoreline position the collapse of a bore is theoretically inferred to be instantaneous, since it is treated as a discontinuity. On a natural beach however, the fully developed bore has a finite width in the (x, z) plane. Consequently, bore collapse in the field was never observed to be instantaneous. This observation has also been reported by MILLER (1968) and YEH and GHAZALI (1988) in reference to their respective laboratory experiments. The width of the bore collapse zone was observed to be very narrow relative to the width of the swash zone.

In general it can be said that the bore collapse process is non-stationary and highly variable in a spatial sense, thus attempts to further investigate the quantitative relationship between the bore velocity and swash velocity with the experimental design used here was not possible.

Uprush

In the following comparison between the theoretical equations for swash and the field data only grain size is shown as an additional experimental variable in each of the figures, since the effects of beach slope can be scaled from the data.

The relationship between the maximum swash height and the initial shoreline velocity is shown in Figure 4, together with the theoretical relationship (10) and the regression model

$$Z_s = \frac{0.65 u_0^2}{2g} \qquad (16)$$

(r = 0.79, 111 df, 1% level). The information provided in the bracket includes the sample correlation coefficient, r, the degrees of freedom for the model, df, and its level of statistical significance. It seems that for the sandy beaches considered here the measured swash height on average reaches to only 65% of the predicted swash height. Note that there is no consistent variation in the data reflecting the variation in grain size between experiments. This result holds for all the swash parameters presented here.

Since the swash probes are stationary, the presence of irregular waves results in a lack of consistency in the measurement locations from one swash cycle to the next. Moreover, the different beach slopes for each experiment means that the raw measurements of shoreline position are not immediately comparable between experiments. For these reasons the measured values of X_s and t have been made non-dimensional using:

$$X_{s^*} = X_s/L_s \quad \text{and} \quad t_* = t/t_{(max)} \qquad (17)$$

where the asterisk denotes the non-dimensional variable, and $t_{(max)}$ and L_s are given by (8) and (9) respectively. This enables the data for all waves and beach slopes to be compared on the same scale.

The relationship between X_{s^*} and t_* is shown

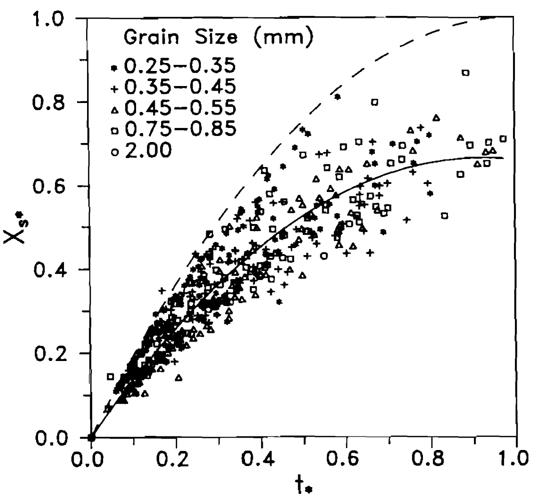

Figure 5. Plot of field data showing the shoreline position (non-dimensional) during the uprush as a function of time (non-dimensional) and grain size. The dashed and solid lines show respectively the theoretical relationship (7) and the regression model (18).

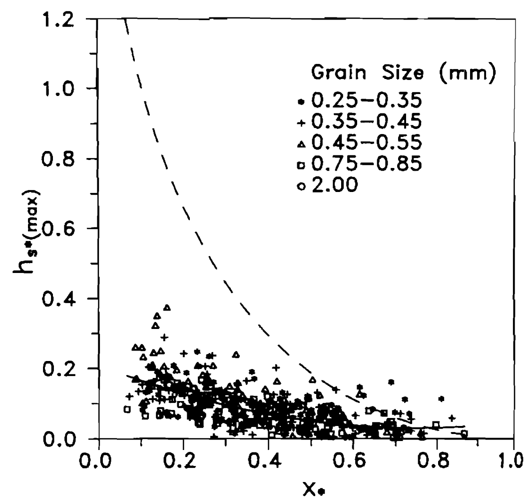

Figure 6. Plot of field data showing the maximum swash depth (non-dimensional) as a function of distance from the initial shoreline position (non-dimensional) and grain size. The dashed and solid lines show respectively the theoretical relationship (15) and the regression model (20).

in Figure 5, together with the theoretical relationship (7) and the regression model

$$X_{s*} = 1.44t_* - 0.78t_*^2 \tag{18}$$

($r = 0.96$, 573 df, 1% level). Only half of the parabola is shown in the figure, because the shoreline position during the backwash could not be accurately determined. Since the best regression model is parabolic and explains 92% of the variance in the measured shoreline position, it is inferred that the shoreline behaviour is successfully predicted by theory. The position of the shoreline is, however, consistently over-predicted by the theory. The degree of over-prediction is relatively constant, with measured X_{s*} values being approximately 70% of that expected.

In order to show the data for all experiments on the same scale the measured values of $h_{s(max)}$ and x were also made non-dimensional using:

$$h_{s*(max)} = h_{s(max)}/Z_s \quad \text{and} \quad x_* = x/L_s \tag{19}$$

where the asterisk denotes the non-dimensional variable, and L_s and Z_s are given by (9) and (10) respectively.

The relationship between $h_{s*(max)}$ and x_* is shown in Figure 6, together with the theoretical relationship (15) and the regression model

$$h_{s*(max)} = 0.21 - 0.48x_* + 0.32x_*^2 \tag{20}$$

($r = 0.63$, 426 df, 1% level). The form of the regression model is again consistent with that expected from theory, but only 40% of the variance in the maximum swash depth is explained by this model. Considering the possibility that errors in estimating the swash depth may reach 50% due to the presence of foam, the fact that a statistically significant relationship exists is promising. However, the magnitude of theoretical over-prediction is generally a factor of 2 or 3 and probably can not be physically accounted for, suggesting that the approximation (11) is a poor predictor. The data did show that the maximum swash depth always occurred before the time that the maximum swash height was reached, which is consistent with (8) and (14).

It is noteworthy that the regression model (20) has a non-zero minima at the position of maximum uprush, $x_* = 1$, where a zero minima is expected on theoretical grounds. Physically, this indicates that the shape of the leading edge, which is apparently influenced greatly by friction, results in a larger than expected swash depth on the upper beach. This observation is discussed further, below.

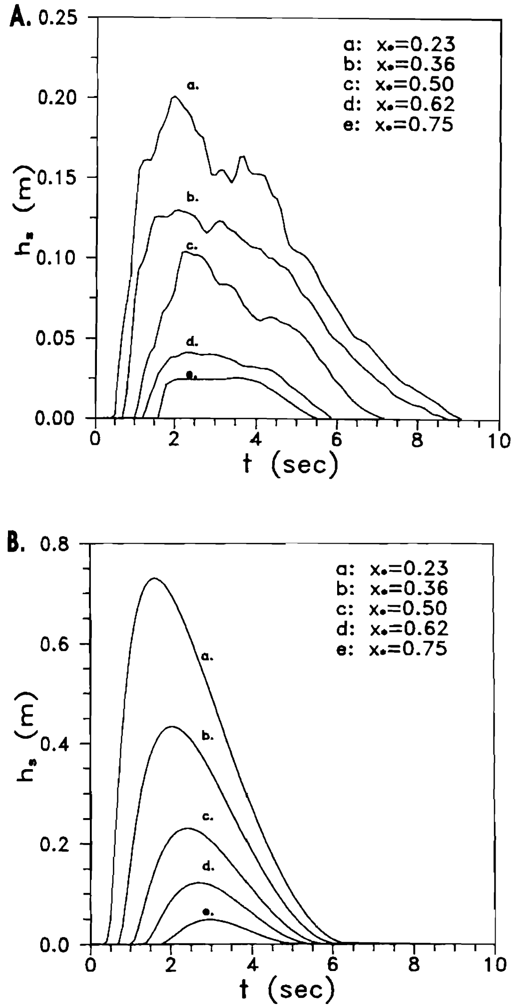

Figure 7. (A) Plot of field data showing the swash depth as a function of time and non-dimensional distance from the initial shoreline position for a single swash cycle. The initial conditions measured for the swash cycle were $u_0 = 4.93$ m sec^{-1} and $\beta = 0.15$. The mean grain diameter of the beach material was 0.44 mm. (B) Plot of the theoretical relationship (11) for the initial conditions corresponding to the field data.

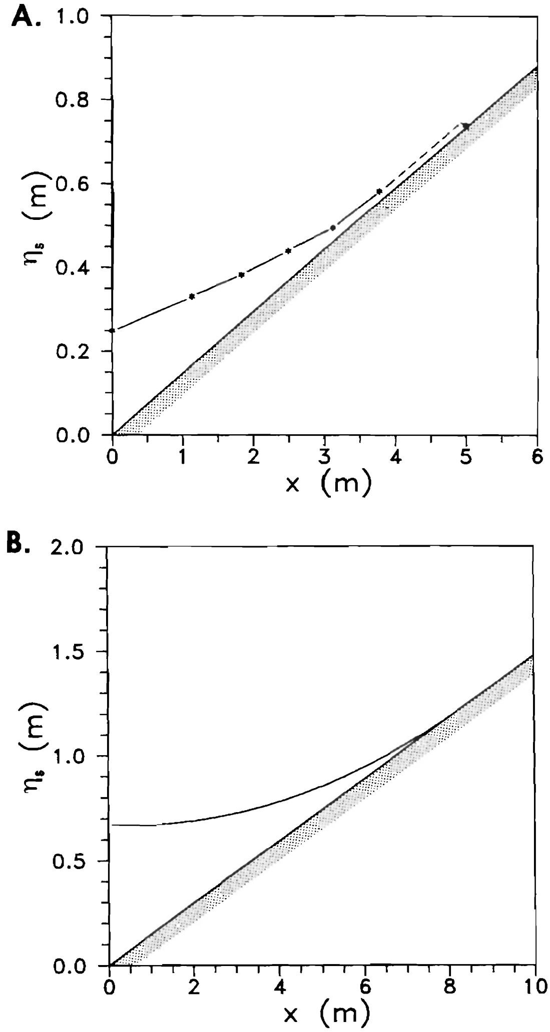

Figure 8. (A) Plot of field data showing the water surface elevation in the swash zone at the time of maximum uprush as function of distance from the initial shoreline position. The asterisks indicate actual measurements and the dashed line is inferred from visual observations and measurements such as those shown in Figure 9. The initial conditions measured for the uprush were $u_0 = 4.93$ m sec^{-1} and $\beta = 0.15$. The mean grain diameter of the beach material was 0.44 mm. (B) Plot of the theoretical relationship (12) for the initial conditions corresponding to the field data.

A typical example of the measured swash depth as a function of time and distance from the initial shoreline position for one particular swash cycle is shown in Figure 7, together with the theoretical prediction given by (11). The gross shape of the $h_s(t)$ curves for both theory and data are similar, but there are some noteworthy differences. The measured swash depth is again over-predicted by a substantial amount during the uprush, which might be expected on the basis of the previous results. However, what is not expected is the pattern that emerges in the backwash. Both the measured backwash duration and the magnitude of the swash depth near the end of the swash cycle are larger than that expected from theory. The significance of these observations will be discussed in the next section.

The water surface profile at the time of maximum uprush for the same swash cycle as that shown in Figure 7 is shown in Figure 8, together with the theoretical prediction given by (12). The tendency shown in Figure 8A for the water surface slope on the upper beach to approach that of the beach slope is entirely consistent with theory. However, the dashed line indicating the water surface profile of the leading edge does not asymptote the beach surface as might be expected. This inferred section of the profile is based on visual observations and the data collected from the Type Two Experiments, of which an example is shown in Figure 9. Although the data in Figure 9 are taken from a different beach to that shown in Figure 8, they are typical of the full range of experimental conditions examined in this study. It appears that in reality the leading edge of the swash lens is blunt; strongly contrasting with the sharp theoretical profile shown in Figure 8B.

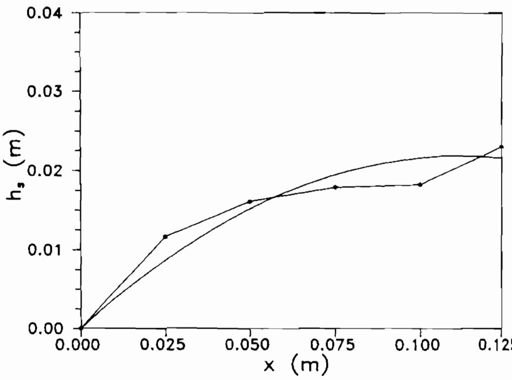

Figure 9. Plot of field data showing the water surface profile of the leading edge of a swash lens during the uprush. The field data are shown by the solid line with asterisks, and the regression model (21) is shown by the plain solid line. The local conditions at the position of measurement were $U_s = 1.00$ m sec^{-1} and $\beta = 0.093$. The mean grain diameter of the beach material was 0.46 mm.

FREEMAN and LEMEHAUTE (1964) showed that the non-linear shallow water theory predicts that the leading edge profile approximates a parabola, if the quadratic stress law is used to model friction in the numerical analysis. Thus a least squares regression model of the form

$$h_s = 0.39x - 1.74x^2 \qquad (21)$$

($r = 0.96$, 4 df, 1% level) is fitted to the data shown in Figure 9. The validity of this model is uncertain due to the experimental error inherent in the data and the inability to combine measurements from several swash cycles to establish its statistical significance. However, other experimental data that display a similar pattern to Figure 9 exist in the literature (*e.g.* MATSUTOMI, 1983). It is suggested therefore, that the true water depth immediately behind the moving shoreline is indeed greater than that expected from the non-linear shallow water theory. This could lead to the measured swash depth approaching and over-taking the predicted swash depth in the later stages of the uprush, as $x_* \rightarrow 1$, and probably explains the decrease in theoretical over-prediction shown in Figure 6.

Backwash

No measurements of the shoreline position could be obtained during the backwash, because the shoreline becomes indistinct as the swash lens thins and develops into a slurry of fluid and sediment. The available data are thus restricted to measurements of the swash depth.

Two types of backwash are evident in the data. Examples of these are shown in Figure 10. Figure 10A shows the $h_s(t)$ curves approaching zero water depth in an obvious sequence. Notice that the curves are nearly parallel in the final stages of the backwash. This indicates physically, that the entire swash lens is decreasing in depth at a similar rate, thus the wedge shape of the lens at the time of maximum uprush (Figure 8) is maintained throughout most of the backwash. In contrast, Figure 10B shows $h_s(t)$ curves that tend to approach zero water depth simultaneously, at least on the lower beach face. This represents the situation where the depth at the seaward end of the swash lens is decreasing at a faster rate than the landward end. Consequently, the swash lens is able to become uniformly shallow over much of its length. This type of backwash lens can often be observed to contain small shock fountains due to the large fluid shear produced in the relatively small depths of water. The concomitant slurry of sand and water renders the concept of a swash depth meaningless, as the top several centimeters of the bed becomes mobile and there is no clear fluid overlying.

It is the first backwash type that most closely

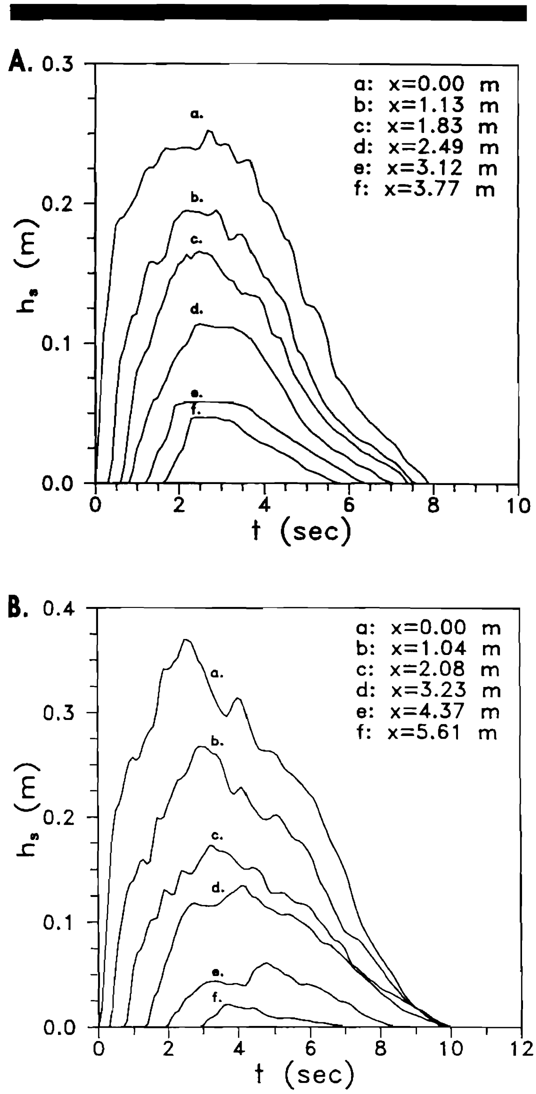

Figure 10. (A) Plot of field data demonstrating the first backwash type discussed in the text. The initial conditions measured for the swash cycle were $u_0 = 4.91$ m sec^{-1} and $\beta = 0.15$. The mean grain diameter of the beach material was 0.44 mm. (B) Plot of field data demonstrating the second backwash type discussed in the text. The initial conditions measured for the swash cycle were $u_0 = 5.05$ m sec^{-1} and $\beta = 0.11$. The mean grain diameter of the beach material was 0.49 mm.

resembles the theoretical behaviour described by (11) (*cf.* Figures 10A and 7B). This agreement is probably fortuitous, however, because the theoretical curves are for a hydraulically smooth and rigid bed and the measurements were essentially of granular-fluid flows strongly influenced by the effects of a rough and movable bed. Furthermore, many of the records displayed the behaviour shown in Figure 10B, indicating that the backwash on natural beaches cannot be described at all well by (11). This is not completely unexpected, since (11) is an approximation which the theory only claims to be valid until the appearance of a retrogressive bore in the backwash.

It was demonstrated that the measured backwash is significantly longer in duration and larger in water depth than that expected from theory. These observations possibly indicate the presence of SHEN and MEYER's (1963) backwash bore. Previous field studies have interpreted the bore to be the stationary hydraulic jump which frequently forms near the initial shoreline position (*e.g.* HO *et al.*, 1963; COWELL, 1982). An interpretation more consistent with SHEN and MEYER's prediction is the surface shear wave that can be observed on relatively small beach slopes (*e.g.* PEREGRINE, 1974), since this type of bore forms up-beach and in the flow interior. This interpretation is still not entirely consistent with theory, however, because the shear wave is typically observed to propagate landward rather than seaward. Another wave form was observed in the backwash during experiments on the larger beach slopes reported here, but was more transient than the shear wave. It tended to be smaller and narrower than the shear wave, often broke before disappearing, and moved seaward with the flow. Regardless of which of these three wave types is most consistent with the expected behaviour of the backwash bore, they all have the effect of increasing the flow depth over that predicted by (11).

Although a backwash bore was frequently observed during the experiments, its representation in the swash depth records is poor. Secondary maxima in the records are common, but they rarely occurred at more than one probe position to establish the bore's direction of propagation. This is probably due to the fact that the bore was restricted to the seaward end of the beach, thus most of the probes were not in its path. Fortunately, on several occasions the occurrence of an unexpectedly large uprush meant that most of the probes were located, relative to the long backwash length, on the lower portion of the beach. One of these occasions is shown in Figure 11. The bore apparently formed somewhere landward of x = 2.18 m, grew in height and then decreased in height (possibly breaking) as it moved down the beach.

This example is entirely consistent with the predictions of SHEN and MEYER (1963), and is the third type of backwash bore described above, rather than the hydraulic jump or surface shear wave.

DISCUSSION

Despite the uncertainties relating to wave behaviour at the initial shoreline position that still remain to be resolved both theoretically and experimentally, flow conditions in the swash zone were found to be reasonably well described by the non-linear shallow water theory. However, the theory was found to consistently over-predict the magnitude of the data. This observation is considered to be a result of friction and infiltration effects not considered in the inviscid theory.

In general the shear stress created by flow over a rough and movable bed causes energy dissipation in the flow and a corresponding reduction in the flow velocity. These friction effects can therefore be expected to reduce the maximum swash height, shoreline displacement and swash depth. Infiltration is also expected to have a reducing effect on these parameters through loss of fluid and hence momentum from the swash lens. The large concentrations of sediment observed to be mobilised during the uprush and the blunt leading edge of the swash lens shown in Figure 9 both attest to the presence of significant bed shear in natural swash zones.

Previous theoretical and laboratory studies have suggested the likely importance of flow resistance in the swash zone (*e.g.* FREEMAN and LEMEHAUTE, 1964; KISHI and SAEKI, 1966; MILLER, 1968; KIRKGOZ, 1981; PACKWOOD, 1983), but until now there has been no suitable field data to indicate its magnitude. If the qualitative agreement between theory and data reported here can be taken as an indication of the theory's ability to describe most of the uprush physics, then some quantitative estimation of the flow resistance is now available. The difference between the magnitude of the data measured and the theoretical prediction may be assumed to represent the total flow resistance induced by the beach face. The data reported here suggest that the flow resistance reduces the maximum swash height to approximately 65% of that expected in the absence of any friction or infiltration.

It is interesting to note that for most of the uprush the shoreline position through time is only reduced to 70% of that expected from theory (Figure 5). The fact that the maximum swash height, which also corresponds to the most landward shoreline position, is reduced to 65% indicates that the flow resistance must increase near the limit of maximum uprush. This seems sensible given that this is where the swash depths are smallest, and hence the effects of friction and infiltration will be most pronounced.

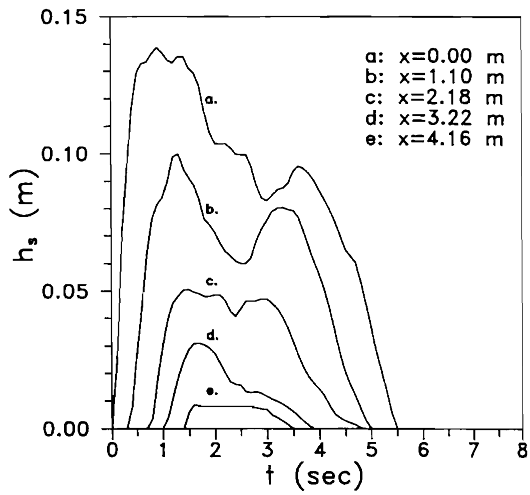

Figure 11. Plot of field data showing the swash depth as a function of time and distance from the initial shoreline position. The existence and propagation seawards of a backwash bore can be seen in the record beginning up beach from x = 2.18 m. The initial conditions measured for the swash cycle were u_0 = 3.71 m sec^{-1} and β = 0.095. The mean grain diameter of the beach material was 0.53 mm.

The fact that variations in grain diameter between experiments had no noticeable effect on the parameters measured is not considered to be contrary to the inferences just made. Most of the experimental grain diameters did not extend beyond the medium sand class of the Wentworth scale. It is quite likely that the natural variability in flow resistance is nearly constant for this range of grain sizes, or small enough to be masked by experimental error (HUGHES, in review).

KOBAYASHI *et al.* (1988) have recently developed a numerical model for surf zone waves and swash, based on a generalised non-linear shallow water theory, and have applied it to limited field data with some success. The model includes energy dissipation due to friction, although the choice of the friction coefficient is somewhat arbitrary at present, due to the paucity of suitable field data. In a forthcoming paper (HUGHES, in review) the inviscid swash equations presented here are developed further by introducing a shear stress term into (5) to account for the observed friction effects. The new equations are then used with the available field data to provide 'measured' estimates of the friction factor for the swash conditions studied here. These results will hopefully lead to an improvement of the available numerical models for swash (*e.g.* KIRKGOZ, 1981; KOBAYASHI *et al.*, 1988), by providing a physically based method for estimating the magnitude of the friction factor.

At present the use of the non-linear shallow water theory is limited to the study of regular waves. Two natural processes confound its application to the problem of irregular waves continuously arriving at the shoreline: the collision between the incoming bore and the backwash, and over-running of an existing swash lens by a following bore. The former results in a hydraulic jump near the initial shoreline position. Methods for calculating energy dissipation in the hydraulic jump can be found in most standard texts on fluid mechanics (*e.g.* STREETER and WYLIE, 1981), but the ultimate effect of a hydraulic jump on the initial shoreline velocity is uncertain. In the case of swash over-running it seems reasonable to expect, from theoretical considerations, that once the following bore crosses the leading edge of the swash lens it will experience bore collapse as it otherwise would at the initial shoreline position. This has been observed during the field experiments. It is not known, however, what effect the moving swash lens has on the initial velocity of the new shoreline.

The problem of bore collapse at the initial shoreline position and at a moving shoreline still requires a great deal more theoretical and experimental research, as the process is not explicitly described by the inviscid SWE. SVENDSEN and MADSEN'S (1984) model of a turbulent bore based on the SWE and two additional equations to formulate the free surface turbulence considers the most significant energy dissipation parameters, but at present its extension to predict the initial shoreline velocity is non-trivial.

Despite the problems that still need to be overcome before realistically applying the non-linear shallow water theory to highly irregular swash, some recent work suggests that the approach holds some promise. MASE (1988) synthesised a time series of irregular swash oscillations using a succession of truncated parabolas. The parabola corresponds to the pattern of shoreline displacement expected from the non-linear shallow water theory and confirmed in this field study. By truncating the parabolas the effects of bore-backwash interaction and bores over-running the swash lens were simulated. MASE calculated the energy spectrum of the time series and found that its characteristics matched well with spectra measured in the field by HUNTLEY *et al.* (1977), also in the presence of irregular swash. This suggests that the swash physics predicted by the non-linear shallow water theory may still determine much of the behaviour of highly irregular swash, despite the chaotic appearance of swash interaction on many natural beaches.

Recent studies examining the stochastic behaviour of swash seem to be successfully predicting the distribution of maximum swash heights on a range of beaches (*e.g.* HOLMAN, 1986; NIELSEN and HANSLOW, 1991). It is worth noting, however, that any attempts to model the interaction of irregular swash, sediment transport and morphological change on the beach face will still require the type of physics-based framework offered by approaches such as the non-linear shallow water theory. N. KOBAYASHI and co-workers (*e.g.* KOBAYASHI *et al.*, 1988) are investigating sediment movement in the swash zone within this framework, and work in progress by D.H. PEREGRINE and G. WATSON (*personal communication*) is expanding this framework to model irregular bores and their ensuing swash.

CONCLUSION

The non-linear shallow water theory's predictions for swash behaviour have been tested using field data collected on a number of sandy beaches. The range of beach slopes and grain sizes studied are 0.093–0.15 and 0.31–2.00 mm respectively. The results are specific to beaches where incident swash processes are dominant and where these processes satisfy certain criteria permitting the application of the theory.

The assumption that underpins the theory and analysis is that no interaction occurs between successive swash cycles. This situation is not strictly observed in the field, however, on reflective and intermediate beach morphologies under swell wave conditions it can be satisfied for a significant portion of the time.

The swash lens following bore collapse on a smooth and impermeable beach is predicted to behave as a rarefaction wave. This implies that the leading fluid element of the lens is never passed by elements from behind, and thus enables the shoreline motion to be modelled through consideration of the leading element alone. Most of the theoretical predictions for the uprush were observed in the field data. Specifically, the following were confirmed:

(1) The maximum swash height is proportional to the square of the initial shoreline velocity.
(2) The locus of shoreline position through time is parabolic during the uprush.
(3) The swash lens climbs the beach and progressively thins with increasing time and distance travelled.
(4) The maximum swash depth at any position on the beach is a quadratic function of its distance from the initial shoreline position.
(5) The maximum swash depth at any position on the beach occurs before the time of maximum uprush.
(6) A retrogressive bore occurs in the backwash.

Shoreline positions during the backwash could not be accurately determined from the field techniques employed. The tendency during the backwash for the decreasing water depth near the receding shoreline to become increasingly loaded with sediment leads to uncertainty in distinguishing between the surface of the swash lens and the beach. Measurements of the water surface at other positions in the backwash showed that the theory is unable to predict much of the observed backwash behaviour, although measurements were made of retrogressive bores in the interior of the backwash.

All of the regression models describing the uprush data were statistically significant at the 1% level, and were all of a similar form to those expected from theory. However, the theory was found to consistently over-predict the magnitude of the data. If it is accepted that the theory adequately describes most of the uprush physics, then energy dissipation due to fluid shear at the bed and loss of momentum due to fluid infiltration into the bed serve to reduce the swash height to approximately 65% of that expected from theory. Interestingly, the success of the inviscid theory in describing the gross flow behaviour of the uprush on a rough and permeable beach face indicates that there is some promise for its extension to study the effects of friction and infiltration on the beach face.

Aspects of the swash cycle that require further research in the light of this study are bore collapse and its effect on the initial shoreline velocity, the inception and propagation of the backwash bore and the behaviour of granular fluid flows in the backwash.

ACKNOWLEDGEMENTS

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□ RESUMEN □

Se considera que la teoría no lineal en aguas bajas, es capaz de describir muchas características del comportamiento de las olas en la zona costera. Para una playa hidráulicamente impermeable y alisada existen un conjunto de soluciones que gobiernan las ecauciones para la zona de lavado que sigue al colpaso. Estas soluciones predicen que la máxima altura de lavado es proporcional al cuadrado de la velocidad inicial. El lugar exacto de la posición de la costa a través del tiempo, es parabólico, la máxima profundidad del lavado en cualquier posición de la playa es una función cuadrática deesa distancia a partir de la posición inicial de la costa. Todas estas predicciones han sido observadas en los datos de campo, colectados a partir de un cierto número de playas de arena en el sudeste de Australia. Sin embargo, la teoría sobreestima consistentemente la magnitud de los parámetros medidos. Se ha presentado una evidencia que sugiere que esta discrepancia se debe a los efectos de fricción e infiltración actuando sobre las lentes de lavado, las cuales inicialmente no son considerados en esta teoría. Aceptando la evidencia disponible, los efectos combinados de fricción e infiltración sobre playas de arena sirve para reducir la máxima altura del lavado en un 65% aproximadamente, de lo esperado según la teoría. Aparte de la sobreestimación de la teoría en lo referente a la magnitud de los parámetros medidos del lavado, el comportamiento del flujo total del ascenso sobre un frente de playa rugoso y permeable parece ser descripto exitosamente por medio de la teoría no viscosa. Existe cierta esperanza, además, de poder modelar existosamente los efectos de friccion e infiltracion dentro del marco teórico. Desafortunadamente la etapa del retroceso del ciclo del lavado no se puede predecir con éxito. Parece ser que es necesario una mejor comprensión del retroceso y el comportamiento del flujo del fluído granular antes de poder modelar el retroceso con cierto éxito.—*Néstor W. Lanfredi, CIC-UNLP, La Plata, Argentina.*

□ ZUSAMMENFASSUNG □

Die nichtlineare Flachwassertheorie wird als geeignet angesehen, viele Formen der Wellendynamik in der Küstenzone zu beschreiben. Zu den vorhandenen Gleichungen für den Vorgang des Auflaufens der Welle, der dem Zusammenbruch der Flutbrandung auf einem hydraulisch glatten und undurchlässigen Strand folgt, gibt es eine Reihe von Lösungen. Sie sagen voraus, daß bei diesem Vorgang die maximale Spülhöhe proportional zu dem Quadrat der anfänglichen Wellengeschwindigkeit ist, daß die Position auf dem Strand mit der Zeit den Verlauf einer Parabel beschreibt, daß die maximale Tiefe des auflaufenden Wassers an jedem beliebigen Ort eine quadratische Funktion der Entfernung von der ursprünglichen Küstenposition ist, daß die größte Spültiefe in jeder beliebigen Position auf dem Strand vor dem Zeitpunkt des größten Auflaufens der Welle erreicht wird und daß sich eine rückschreitende Brandungswelle beim rücklaufenden Wasser formt. Alle diese Voraussagen wurden mit Felduntersuchungen an einer Reihe von Sandstränden in Südost-Australien als zutreffend belegt. Allerdings übertrafen stets die nach der Theorie errechneten Parameter die tatsächlich gemessenen. Es werden Belege angeführt, daß diese Diskrepanz auf die bisher nicht in die Theorie eingehenden Faktoren Reibung und Infiltration, die auf die Wasserlinse beim Auflaufen wirken, zurückzuführen ist. Falls die zur Verfügung stehenden Belege akzeptiert werden, dann bewirkt die Kombination von Reibung und Infiltration an einem Sandstrand eine maximale Verminderung der Höhe des Auflaufens auf ca. 65% des aufgrund der Theorie zu erwartenden Wertes. Abgesehen von der theoretischen Überschätzung der Größen für die gemessenen Parameter, scheint die Theorie das generelle Fließverhalten der auf einen rauhen und durchlässigen nassen Strand auflaufenden Welle erfolgreich zu beschreiben. Daher ergibt sich die Möglichkeit, nun auch den Einfluß von Reibung und Infiltration im Rahmen dieser Theorie richtig zu modellieren. Leider wird die Phase des rücklaufenden Wassers im Wellenzyklus nicht so gut vorausberechnet. Offenbar müßten dafür sowohl die Rücklaufwelle als auch das Verhalten von körnig-flüssigen Strömen besser verstanden werden.—*Helmut Brückner, Department of Geography, University of Marburg, Deutschhausstr. 10, D-3550 Marburg, Germany.*