CHAPTER 104

SURF ZONE MEASUREMENTS OF SUSPENDED SEDIMENT

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ABSTRACT

Suspended sediment concentration was measured in approximately 250 breaking waves on undeveloped beaches near Price Inlet, South Carolina, U.S.A., using portable in situ bulk water samplers. As many as 10 instantaneous 2-liter water volumes were obtained in each wave for a total of 1500 samples. Concentrations of suspended sediment were determined at fixed intervals of 10, 30, 60 and 100 cm above the bed for various surf zone positions relative to the breakpoint. The majority of waves sampled during 22 days in June and July, 1977 were relatively long crested, smooth, spilling to plunging in form, with breaker heights ranging from 20 to 150 cm. Surf zone process variables measured included breaker height and depth, breaker type, wave period, surface longshore current velocity, wind velocity and direction.

Scatter plots of mean concentration against various process parameters indicate the amount of sediment entrained in breaking waves is primarily a function of elevation above the bed, breaker type, breaker height and distance from the breakpoint. Concentration ranged over 3 orders of magnitude up to 10 gm/l, but varied less than 1 order for samples collected under similar conditions with regard to elevation and breaker type. Plunging breakers generally entrain 1 order more sediment than spilling breakers equal in height. Despite considerable scatter, these data indicate concentration decreases with increasing wave height for waves 50 to 150 cm high, suggesting that small waves can be important in the transport of sand on gently-sloping open coasts.

INTRODUCTION

Over 1500 instantaneous suspended sediment concentrations have been determined from water samples collected in the surf zone near Price Inlet, South Carolina, U.S.A. The purpose of this study was to determine the spatial distribution of suspended sediment near the breakpoint under various wave conditions in order to identify the wave parameters which control the amount of sediment entrained from the bed. This work represents one of several experiments conducted by the Coastal Research Division of the University of South Carolina designed to increase our understanding of sediment entrainment and transport processes in waves and eventually to construct a predictive model of suspended sediment concentration in the surf zone.

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METHODS FOR MEASURING SUSPENDED SEDIMENT CONCENTRATION

        Only a few workers have attempted to measure concentration of sus-
pended sediment in breaking waves, undoubtedly due to the relative dif-
ficulty of sampling in a high energy environment. Three basic methods
for measuring concentration in oscillatory flows have been used: pump
systems for obtaining a time-integrated sample of water and sediment
(Watts, 1953; Fairchild, 1972, 1977; and Coakley, et al., 1978, this
volume); in situ collecting traps for obtaining relatively instantaneous
bulk water samples (Kana, 1976; Inman, 1977); and indirect measures
which relate turbidity to light attenuation, back scatter of light, or
gamma absorption (Hom-ma, et al., 1975; Hattori, 1969; Horikawa and Wa-
tanabe, 1970; Kennedy and Locher, 1972; Basinski and Lewandowski, 1974;
Brenninkmeyer, 1976a; and Leonard and Brenninkmeyer, 1978, this volume).
There are obviously certain disadvantages to any of these techniques,
most important of which is the influence of the sampling apparatus on
the flow field. Any device which remains fixed to the bed, or utilizes
a supporting structure or pier, is likely to monitor artificially-in-
duced suspensions (Inman, 1977).

        Pump samplers were not suitable for the present study because
they provide time-averaged water samples making it difficult to deter-
mine the effect of a single wave on sediment suspension. Since concen-
tration generally fluctuates at a period approximating that of the in-
cident wave field, relatively instantaneous values were required.

        Indirect monitors of concentration, such as the almometer (Bren-
ninkmeyer, 1976a), have the advantage of providing detailed time series
information on turbidity changes, but most of these devices are diffi-
cult to calibrate for field use. Such external conditions as cloud
cover, air entrainment in the surf zone, and the presence of varying
amounts of organic matter in the water column, affect turbidity and,
therefore, the output of these devices. Also, in some cases, the
threshold for detecting sediment bursts from the bed is significantly
higher than the typical concentrations found in the surf zone by Watts
(1953) in California, or Kana (1977) in South Carolina.

        According to Inman (1977), the best way of overcoming the limita-
tions of presently available suspended sediment samplers is by using
portable in situ samplers activated by swimmers in conjunction with
remote recording turbidity sensors. This combination may be ideal,
but it is difficult to coordinate and expensive to deploy. However,
for the past 3 years, we have used a portable in situ water sampler
which has proven to be an efficient and inexpensive means of obtaining
suspended sediment samples in the surf zone under a variety of wave
conditions. Concentrations obtained directly from in situ water samples
have been combined with littoral observations to estimate suspended sedi-
ment transport rates along two undeveloped beaches (Kana, 1977).

        The apparatus used in the present study collects several closely
spaced simultaneous water samples in a vertical array above the bed
(Kana, 1976). It consists of a 2 meter-long mounting pole, support
brackets and several 2-liter cast acrylic bottles closed off by hinged

doors (Fig. 1). To ready the sampler for use, the operator opens the bottle doors and attaches them to a trigger assembly on the mounting pole, similar to rigging a Van Dorn-type water sampler. Then as the bottles are held open, the device is carried into the surf zone and positioned vertically above the bed until the sampling instant. At the desired sampling time, the apparatus is thrust into the bed, forcing the trigger open and allowing the bottles to shut simultaneously, trapping each sample. The device has a relatively fast response time of less than one-half second, remaining off the bed until the sampling instant. Tests have shown that the collecting bottles are drawn shut before sediment thrown up by the apparatus reaches each sampling position. The typical array of samples collected in this study were centered at 10, 30, 60 and 100 cm above the bed. Because of the relatively broad, stubby shape of each collecting bottle, the lowermost sample obtains sediment suspended between 4 and 16 cm above the bottom. Inman (1977) has recently developed a portable device for "coring" the water column to obtain a similar vertical array of instantaneous water samples; however, detailed results were not available in time to be included in this report.

PREVIOUS RESULTS

It is generally recognized from laboratory studies that in oscillatory flow, suspended sediment concentration decreases exponentially above the bed (Hattori, 1971; Kennedy and Locher, 1972; and MacDonald, 1977). Field measurements in the surf zone by Inman (1977; Fig. 5) and Kana (1977; Figure 5) tend to confirm this relation. A relatively constant suspension wash load of fine-grained particles exists throughout the water column in the nearshore. However, in the breaker and swash zones, intermittent suspensions of relatively coarse bed material are thrown up by waves to cause the observed vertical distribution of concentration. The frequency and magnitude of these intermittent suspensions are of primary interest because of their importance in the transport of sand on beaches. In general, the timing of bursts of sediment from the bed corresponds to the time of wave breaking, with some delay as the particles lag behind the water motion (Hattori, 1969; Brenninkmeyer, 1976b).

Fairchild (1972), working from ocean piers at Ventnor, N. J. and Nags Head, N. C., has measured a slight increase in concentration with breaker height and a decrease away from the breakpoint for time-integrated pump samples. Additionally, he has shown that concentration increases with the ratio of breaker height to breaker depth and is more variable with low waves than high. His samples were collected in waves ranging from 40 to 120 cm, yielding concentrations up to 4.0 parts per thousand. The sampler intake was varied between 8 cm and 75 cm above the bed. Since most of the samples were pumped over a 3 minute time period, it is difficult to isolate the effect of a single wave and establish any quantitative relationships from these data. However, Fairchild was apparently correct in concluding that suspended sediment concentration is a function of elevation above the bed, wave height and position in the surf zone.

Brenninkmeyer (1976b), using arrays of photoelectric sensors in the surf at Point Mugu, California, found that the zone of maximum suspension occurs near the stillwater level in the swash zone. He reported that suspensions of sand more than 15 cm above the bed are rare in the outer surf zone and appear to be influenced by the stage of the tide and the elevation of the ground water table. Bursts of sediment from the bed or "sand fountains" have durations of the order 2 to 10 seconds, apparently corresponding to the period of incident waves.

Kana (1977) reported a dependency of concentration on elevation above the bed and breaker type, based on instantaneous in situ bulk water samples collected along two South Carolina beaches. Using a visual classification, he reported that plunging-type waves entrain almost one order more sediment than spilling breakers.

None of these studies is complete enough to establish a quantitative relationship between suspended sediment concentration and commonly measured surf parameters. However, they provide a basis to continue research designed to isolate and identify the important factors controlling the entrainment of sediment in the surf zone. The present paper is, at most, an attempt to describe some relations of common surf parameters to suspended sediment concentration under a variety of moderate wave conditions. As such, it applies to a relatively specific wave climate, beach morphology, sediment size and bed packing.

STUDY AREA

The field measurements for this study were obtained at two beach sites, each approximately 2 km from Price Inlet, on Bulls Island and Capers Island, South Carolina (Fig. 2). This portion of the South Carolina coast is under the influence of dominant waves from the northeast, causing net longshore transport to the south (estimated rate is 1.2 – 1.5 x 10^5 m^3/yr; Kana, 1977). Wave energy is moderate with breaker heights ranging from 20 to 160 cm under non-storm conditions, with a mean of 60 cm. The beaches at these two sites are composed of well-sorted, fine sand (mean diameter = 0.22 mm) and are gently sloping and relatively featureless (mean beach face slope = 0.018). During average swell conditions, the surf zone is approximately 50 meters wide, but due to the mean tide range of 1.5 meters, a much wider portion of the beach face is periodically exposed to the impact of breaking waves. The bed in the active surf zone is tightly compacted and rarely exhibits small scale bedforms. Slope changes along the beach face are minor and generally controlled by the formation of low amplitude ridges or bars parallel to shore.

EXPERIMENTAL DESIGN

During 22 sampling days in June and July, 1977, multiple arrays of water samples were collected in the littoral zone near Price Inlet, South Carolina, during a variety of swell conditions using the sampler in Figure 1. Up to three arrays providing as many as 10 water samples were used in the same wave to detect suspended sediment concentrations

Figure 1. Apparatus used to collect water samples in the surf zone. A 2 m-long pole supporting several 2 l. bottles is emplaced vertically in the surf zone. When thrust into the bed, a foot pad moves the trigger assembly up, simultaneously tripping each bottle. Top two bottles are rigged for sampling. Bottom bottles are in the tripped position.
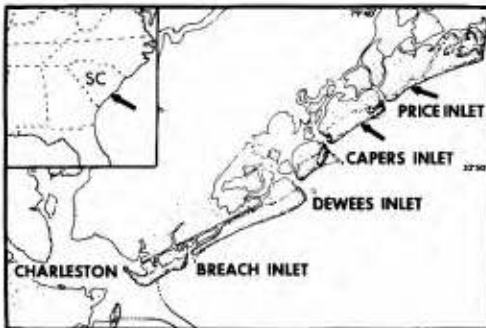

Figure 2. Study area near Charleston, South Carolina, U.S.A. Suspended sediment samples were collected at stations located along two undeveloped beaches near Price Inlet (arrows).

across the surf zone and along individual wave crests. A four-to six-
man field team was required in order to simultaneously collect the water
samples, make littoral process observations, and photograph each wave
sampled.

     Two ranges were established at the experiment sites and periodi-
cally surveyed to the low tide breaker line to establish the beach slope
at each sampling point. Each day, stakes were set throughout the surf
zone as reference points for sampling location and wave position. Each
suspended sediment sample was positioned in relation to: 1) the bed, by
means of the sampling apparatus, 2) a bench mark on land, by means of
the reference stakes, 3) the wave breakpoint, by measuring the distance
seaward or landward to each array, and 4) the time of passage of each
wave sampled. Figure 3 is a sketch of a typical sampling arrangement.
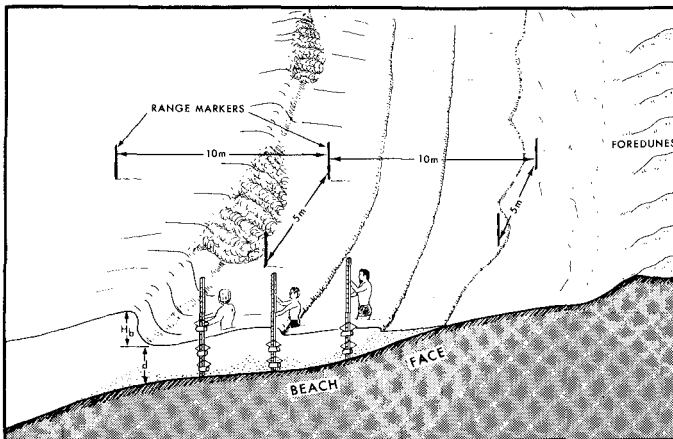

     Figure 3. Sketch of the sampling arrangement showing
        samplers in place. Operators stood downdrift from
        sample point holding apparatus above bed until
        sampling instant.

     In order to minimize the number of variables affecting the distri-
bution of concentration, sampling was performed during swell conditions
with wind velocities less than 5 m/s. Generally at these beach sites,
waves are more "classically" formed and long crested in the morning be-
fore the diurnal sea breeze is established. As onshore wind velocity
increases, wave crests become shorter and more irregular, making it dif-
ficult to distinguish the breakpoint. The beaches at these two sites
were chosen for the experiment because their profiles are generally
featureless, small scale bed forms are essentially nonexistent, and
they are away from any artificial structures which may influence tur-
bidity.

All samples reported herein were collected approximately 2 seconds after the passage of the wave bore by each sampler. Previous results indicate that, in general, the maximum concentration at a point occurs just after the passage of a wave (Kana, 1977). Thus, with 3 operators, it was possible to follow one wave toward shore and, to some extent, determine the change in concentration across the surf zone. Multiple arrays were also collected along individual wave crests to determine the range of variability of concentration within a single wave. Each wave sampled was photographed at several positions during breaking to maintain a record of wave types and provide a means of checking visual estimates of height and depth. A typical photographic sequence is shown in Figure 4.

The following surf parameters were measured for each sample array:

1. Breaker height (H_b) and water depth at breaking (d) - visually, by means of a graduate staff held in place at the breakpoint and checked by scaling photographs taken during sampling. Limit of error $\pm$ 10 cm.

2. Wave period (T) - by averaging the time of travel between the wave crest prior to, and the crest following, the wave sampled. Limit of error $\pm$ 1 second.

3. Surface longshore current velocity at mid-surf position (V) - by timing the travel of small floats between range markers set 10 m apart in the alongshore direction.

4. Breaker angle (α_b) - visually, by means of a protractor, sighting the acute angle between wave crest and shoreline. Limit of error $\pm$ 2 degrees.

5. Breaker type - qualitatively, by visual observations in the field, verified by photos taken while sampling and checked against various breaker-type parameters (e.g., Galvin, 1968; Battjes, 1974).

6. Wind velocity and direction - by means of a hand-held anemo-meter.

Suspended sediment samples were processed by normal filtration techniques to determine concentration as a weight per unit volume (gm/l).

Using up to 3 samplers in each wave, over 250 individual waves were sampled during the study yielding approximately 1500 concentration values. Over 1000 of the samples were collected at 10 and 30 cm above the bed.

Table 1 summarizes the range of surf conditions and number of samples by wave type and wave height collected during the experiment.

Figure 4. Four successive photographs
  of one of the breaking waves sampled
  at 3 positions inside the surf zone.
  Arrays of suspended sediment samples
  taken 3 m, 7 m, and 10 m landward of
  the breakpoint.   Concentrations are
  listed below.

A. Wave beginning to break 3 m seaward
  of sampler operator #1.
  H_b= 90 cm; d = 95 cm; T = 8 s; V =
  0 cm/s; m = 0.011; breaker type:
  spilling; Time = 0 s.

B. Wave fully broken, bore at Opera-
  tor #1.
  Bore height = 70 cm; Depth under
  bore = 90 cm; Time ~ 1 s.

C. Bore approaching operator #2.
  Bore height = 60 cm; Depth =
  65 cm; Time ~ 2½ s.
  Just before sampling instant
  array #1 (seawardmost).

D. Bore at operator #3.
  Bore height = 55 cm; Depth =
  60 cm; Time ~ 4 s.
  Just before sampling instant Array #2.

Results:

Array #	Elev. above bed (cm)	Conc. (gm/l)
1	60	.135
	30	.256
	10	.329
2	30	.261
	10	.234
3	30	.170
	10	.231

A.

B.

C.

D.

TABLE 1

Breaker height	Breaker Type - # Waves Sampled			# Vertical arrays of*
Hb (cm)	Spilling	Spill/Plunge	Plunging	susp. sediment samples
0-35	5	4	2	29
35-45	7	1	3	32
45-55	15	2	5	56
55-65	12	4	1	46
65-75	15	8	10	92
75-85	29	6	7	118
85-95	13	11	18	115
95-105	8	9	5	63
105-115	10	3	2	45
115-125	6	2	1	27
125-160	11	0	0	33
Totals	131	50	54	656

* 3 vertical arrays of 1 to 4 samples each were collected in each
  wave to yield a total of approximately 1500 concentration values.

RESULTS

Previously reported field results by Watts (1953), Fairchild
(1972) and Kana (1977) have shown that the concentration of suspended
sand in the surf zone can vary by several orders of magnitude.
Therefore, it is necessary to compare samples collected under similar
conditions with regard to wave position and height above the bed in
order to determine the effect of individual waves. By grouping samples
according to elevation, breaker type or distance from the breakpoint,
it is possible to eliminate much of this variation. As a first attempt
at establishing the relation between common surf parameters and concen-
tration, it was decided that a comparison of mean values obtained under
similar conditions was the best (and perhaps only) way of isolating any
trends. There will be no attempt in this paper to rigorously test
these relationships. Instead, they are presented as a description of
a given set of field conditions.

Plotted on a log scale, suspended sediment concentration is nor-
mally distributed by sample elevation for the data set reported here-
in (Fig. 5). From Figure 5, it can be seen that the mean concentra-
tion 10 cm above the bed is approximately 2 times higher than the mean
concentration at 30 cm. The range of concentrations at each sample
elevation spans roughly 2 orders of magnitude.

Figure 6 shows mean suspended sediment concentration by elevation
for three breaker types classified by visual and photographic inter-
pretation. Two dominant wave types, plunging and spilling, occur at
the experiment sites. However, we identified and plotted an inter-
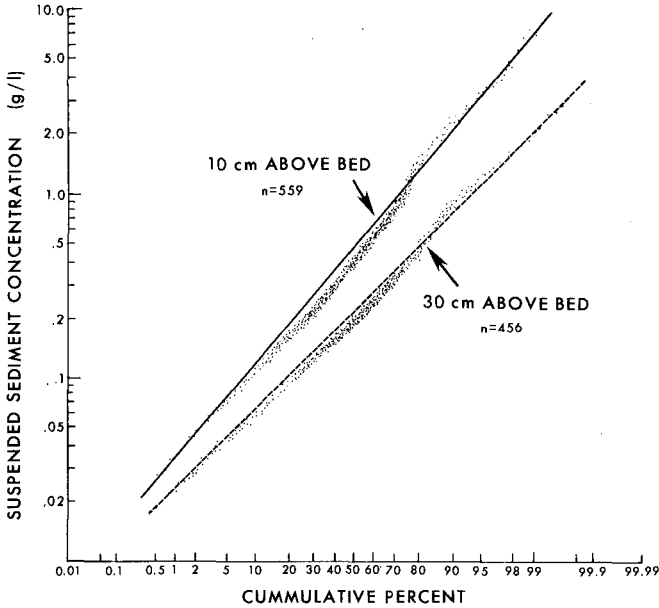mediate type exhibiting characteristics of both spilling and plunging

.Figure 5.   Normal probability plot of concentration for
all samples collected 10 cm and 30 cm above the bed
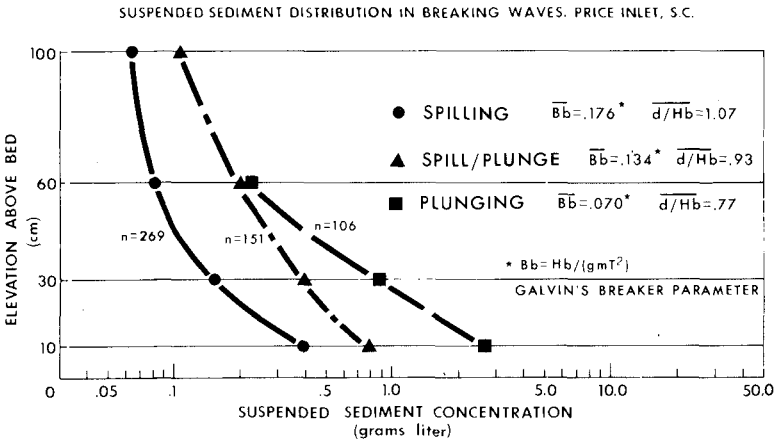irrespective of breaker types.

Figure 6.   Suspended sediment distribution in the outer surf zone
between 1 and 10 m landward of the breakpoint. Mean concentra-
tions are plotted by elevation above the bed for spilling and
plunging type breakers. An intermediate wave type exhibiting
characteristics of spilling and plunging waves is also plotted
(triangles).

waves. The visual classification of wave types tends to agree with
Galvin's (1968) breaker classification, which is given by a dimen-
sionless parameter, (B_b), based on wave steepness and beach slope[*].
Galvin reports a cut off from spilling to plunging waves at B_b =
0.068 versus 0.070 for these data. The depth at breaking generally
decreases from spilling to plunging waves, and this agrees with mean
values of the ratio breaker depth to height, (d/H_b), listed in Fig. 6.
Note that plunging waves, on average, entrain almost one order more
sediment than spilling breakers. Concentration decreases exponenti-
ally up to 60 cm above the bed, then appears to reach a constant value,
reflecting the type of suspension: intermittent close to the bed, re-
sulting from periodic bursts of coarse, bed material; continuous
near the surface, due to the dominance of suspended wash load.

Since breaker type is an important factor controlling the mag-
nitude of intermittent bursts of sand from the bed, it is desirable
to test concentration against parameters which quantify the variation
in wave type. No universally accepted breaker classification exists,
but several have been proposed. Probably the most widely known are
Galvin's (1968), which was already mentioned, and Battjes' (1974),
which is also based on wave steepness and beach slope. Based on
laboratory waves, Galvin has determined cutoffs between spillings
and plunging waves at B_b = 0.068 and for plunging and collapsing
waves at B_b = 0.003. Galvin's inshore parameter is plotted against
mean suspended sediment concentration for samples collected 10 cm
above the bed (Fig. 7). There is a general trend of increasing con-
centration from spilling to plunging waves, but due to considerable
scatter, and the relatively flat slope of the regression line, this
relation is not satisfactory as a predictor of concentration for these
data.

The poor fit of the data to Galvin's breaker classification may
be due to the dependence of B_b on wave period (T). A plot of concen-
tration versus period shows essentially no dependence of suspended
sediment on T (Fig. 8). This suggests that the periodicity of waves
has little effect on sediment entrainment for this range of waves.
This is not surprising, considering the characteristics of waves as
they are transformed at breaking. Munk (1949) recognized that wave
length, a function of T, has little to do with the shape of waves
near the breakpoint since waves in very shallow water commonly have
long, shallow troughs and steep, sharp crests. Consequently, he re-
commended applying solitary wave theory for describing waves near
breaking. This theory differs from the classical Airy or Stokes

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[*] B_b is Galvin's _inshore_ parameter given by $B = H_b/(gmT^2)$, where
  H_b is breaker height; g is acceleration of gravity; m is beach
  slope; and T is wave period.

Figure 7. Mean concentration at 10
  cm above the bed versus Galvin's
  (1968) inshore breaker type param-
  eter ($B_b = H_b/(gmT^2)$). The defined
  cut off between spilling and plung-
  ing waves is 0.063. Although there
  is a trend toward high concentra-
  tions in plunging waves, this param-
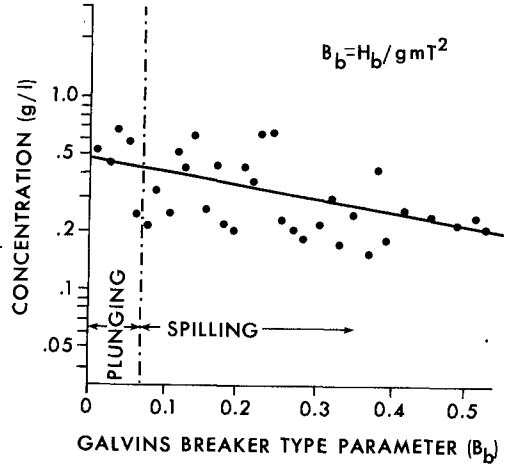 eter is not an adequate predictor
  for these data.

Figure 8. Mean concentration at
  10 cm above the bed versus
  wave period for plunging and
  spilling breakers. Bars on
  each point represent the
  range in concentration values
  to $\pm$ 1 standard deviation.
  Suspended sediment appears to
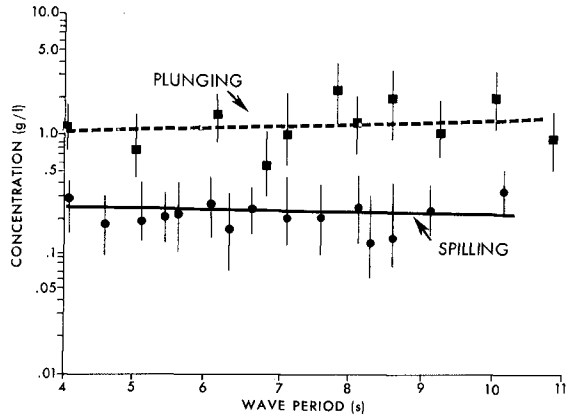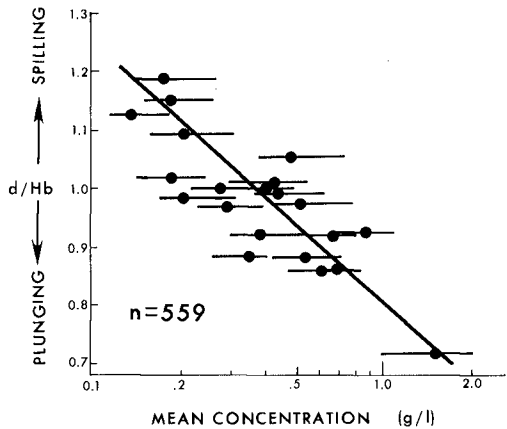 be independent of wave period
  for moderate wave conditions.

Figure 9. Mean concentration at
  10 cm versus the ratio of breaker
  depth (d/H_b). Bars on each point
  are $\pm$ 1 standard deviation. This
  parameter, independent of wave
  period, is useful for distin-
  guishing breaker types and pre-
  dicting concentration.

wave theories because it contains only one fundamental parameter indepen-
dent of wave length: relative wave height, or the ratio, H_b/d.

    In Figure 9, d/H_b has been plotted against mean concentration
for the 10 cm above the bed samples. There is still considerable scat-
ter in the plot, but the data show better separation of breaker types
by this parameter alone. Relative wave height, which is independent of
wave steepness, appears more useful for classifying the present set of
waves. Bars on each data point represent the range of variation in con-
centration to $\pm$ 1 standard deviation.

    It would be useful to establish a relation between wave height
and suspended sediment concentration for purposes of prediction, since
H_b is a commonly measured surf parameter. Fairchild (1972) reported an
increase in concentration with wave height, and it is commonly believed
that sediment suspension increases directly with wave energy. The data
in Figure 10, breaker height versus concentration by wave type, do not
support this contention. The means for samples collected 10 cm above
the bed show a clear distinction between breaker types, but the shape
of each curve is different. Figure 10 shows an increase in concentra-
tion for spilling waves up to approximately 90 cm, then a significant
decrease for higher waves up to 150 cm. This suggests a concentration
maximum in wave heights between 50 and 90 cm for moderate swell condi-
tions. Plunging waves, on the other hand, show a generally continuous
decrease in concentration with increasing breaker height. It is not
clear why this unexpected result occurs, but it may be related to the
increased interaction of the swash uprush and backrush with smaller
waves. The width of the surf zone is a function of breaker height
such that higher waves tend to break in deeper water considerably sea-
ward of the zone of maximum backrush. This is especially true for re-
latively flat beaches similar to those in South Carolina. If concen-
trations corresponding to waves less than 50 cm in height are not con-
sidered, there remains a trend of decreasing concentration with H_b
for both breaker types.

    Concentration is plotted against distance from the breakpoint
in Figure 11, showing the variation in mean values across the surf
zone. Again, there is a clear distinction between breaker types, with
plunging waves entraining higher amounts of sediment. Spilling waves
show a sudden increase in concentration within 1-2 m landward of the
breakpoint and then appear to maintain a relatively steady suspension
across the surf zone. Plunging waves similarly show a rapid increase
in concentration just landward of the breakpoint, then a gradual de-
crease with distance toward shore. The shapes of these distributions
seem reasonable if one considers that plunging waves dissipate their
energy more rapidly (Führböter, 1970), and, consequently, should show
a peak close to the breakpoint.

    Other parameters tested against concentration included wind
velocity, longshore current velocity and beach slope; however, none
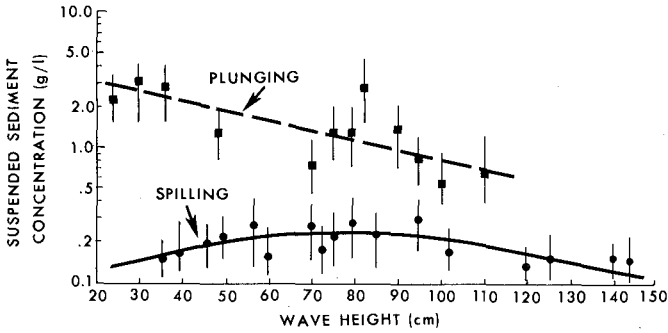was found to be a useful predictor for these data. This is due in

Figure 10.   The variation in concentration with wave height for
spilling and plunging waves.   In general, suspended sediment
decreases with increasing wave height during moderate wave
conditions on gently sloping (m = 0.018), fine-grained beaches.
Plunging waves entrain approximately 1 order more sediment than
spilling waves equal in height.

Figure 11.   Distribution of
mean concentration at 10
cm above the bed, rela-
tive to wave breakpoint.
Suspended sediment in-
creases sharply 1-2 m
landward of the break-
point, then remains re-
latively constant in
spilling waves.   Plung-
ing waves tend to peak
close to the breakpoint
then gradually decrease
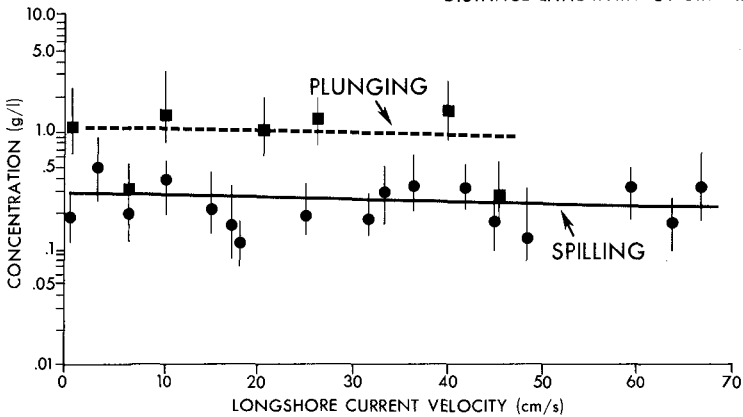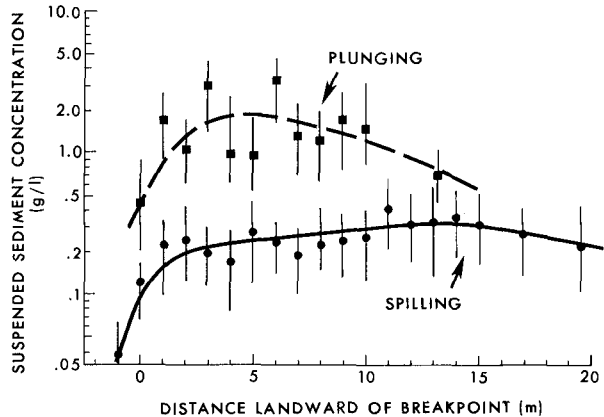due to more rapid ener-
gy dissipation.

Figure 12.   Suspended sediment concentration appears to be in-
dependent of longshore current velocity for these data.
Samples were collected during a variety of moderate wave
conditions over 22 days.

part to the moderate weather conditions prevailing during the study
and the attempt to sample only during swell conditions. Beach slope
remained relatively constant during the experiment, and surface wind
velocity never exceeded 5 m/s. Longshore currents were variable, but
as shown in Figure 12, they do not explain concentration variability
for these data. This is probably due to the imprecision of our cur-
rent measurements, as much as the relatively low velocities recorded.
It is probable that wind and longshore current velocity become very
important during storms.

DISCUSSION

        Despite the lack of measurements during storms (a perennial
omission with experiments in the surf zone), a major problem in the
present study is the range of variability of wave conditions even
during relatively ideal swell conditions. To isolate the effect of a
single process variable on concentration, repeat sampling under
identical conditions is necessary. This may be an impossible task,
since not only do successive waves vary in form on a given day, but
individual waves exhibit considerable variation along their crests.
This is further magnified by small scale changes in bottom topography.
It was the intention in this experiment to sample well formed, swell
waves with easily definable breakpoints to minimize the influence of
such secondary effects as surface wind stress or small scale bedforms.
Obviously, these external factors can be important. Even under con-
trolled situations in the laboratory, suspended sediment can be as
variable as turbulent flows.

        Although concentration varies by several orders of magnitude
in the surf zone, these data show that samples taken under similar
conditions with respect to elevation, breaker type or wave height
vary by much less. As indicated by the ranges in each figure, the
standard deviation around the means is significantly less than one
order of magnitude for most of these samples. Thus, with increased
control over sampling, it should be possible to define a smaller
range of concentration values for a given set of wave and beach con-
ditions.

        These results tend to confirm several widely held notions con-
cerning sediment suspension in the surf zone, including the dependence
of concentration on elevation above the bed and breaker type. But at
the same time, they present relations which are not easily explained
based on our present understanding, especially the decrease in concen-
tration with breaker height. A possible explanation for the results
reported herein may be found in the laboratory studies of Miller (1976),
who photographed the entrainment of air in breaking waves. Figure 13,
reproduced from Miller's work, shows the distribution of air bubbles
entrained in plunging and spilling waves. Note that in spilling break-
ers, bubbles remain near the surface; whereas, in plunging waves, air
is entrained all the way to the bed. Since this distribution of bub-
bles is an indication of turbulence, it is evident that plunging waves

will effect sediment entrainment from the bed more readily than spil-
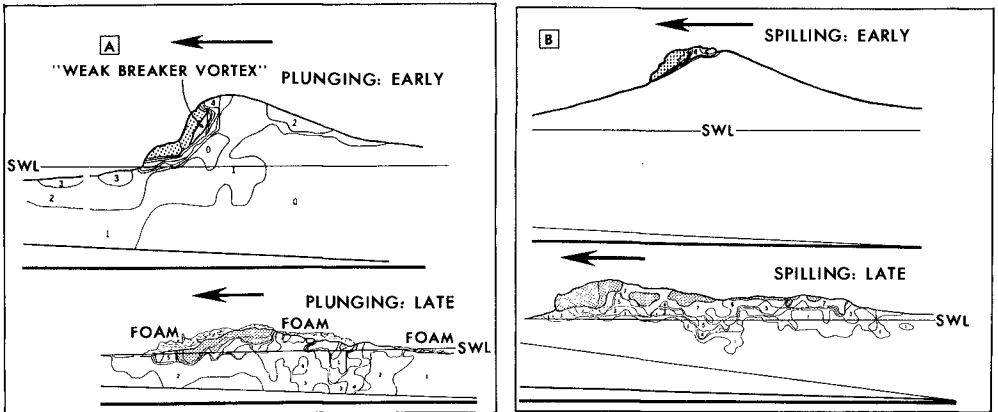ling breakers. The concentration data of the present study verify
this.

Figure 13. Cross-sectional contour diagrams of bubble concentration
   in plunging (A) and spilling (B) breakers. Numbers represent per-
   centage estimate of the number of 1 mm scale units containing one
   or more bubbles (on a scale of 1 to 10). A 5 means 50% of the scale
   units contain bubbles, a 10 represents 100% bubble concentration.
   Note that bubbles penetrate to the bed in plunging waves but remain
   close to the surface in spillers. This suggests more turbulence
   reaches the bed in plunging waves contributing to the observed high-
   er concentrations of suspended sediment for this breaker type (Miller,
   1976).

Miller's diagrams may also explain lower concentrations with increas-
ing breaker heights. If one considers that waves generally break at
a depth approximately equal to wave height, turbulence in higher
waves must penetrate deeper water to impact the bed. Just as the air
bubbles in Miller's spilling waves remain near the surface, the energy
to suspend sediment may move away from the bed as water depth increases
with higher waves. Although wave energy increases with breaker height,
it may be counteracted by the absorbing "cushion" of water which in-
creases with trough depth. Also, on gently sloping coastlines like
South Carolina, the largest waves tend to spill, gradually dissipat-
ing their energy over a wider surf zone.

     An important implication of these results is the apparently sig-
nificant role of smaller waves on sediment suspension. During moderate
swell conditions, there may be less sediment moved by the largest waves
 breaking in the outer surf zone than is moved by small secondary waves
close to the swash zone. And, as Brenninkmeyer (1966) suggests, sedi-
ment suspension may be the dominant mode of transport only in the in-
ner surf zone.

Inman (1977) has stated that studies of suspended sediment in the surf zone are generally deficient due to the lack of simultaneous measurements of the velocity and turbulence fields. While this is certainly true, the problem will remain until better measurement techniques are developed. Obtaining simultaneous, accurate measurements of the suspended load and velocity field is a formidable and expensive proposition. The techniques used in the present study offer a less rigorous but efficient and inexpensive method of studying suspended sediment in moderate wave conditions.

CONCLUSIONS

Based on the above results for plunging and spilling waves, under moderate swell conditions, the following conclusions are offered:

1. Suspended sediment concentration in the breaker zone is primarily dependent on elevation above the bed, breaker type, wave height and distance from the breakpoint.

2. Concentration decreases exponentially above the bottom to approximately 60 cm elevation as a function of the intermittent suspension of coarse sediment from the bed.

3. Relative breaker height (d/H_b) is useful for quantifying breaker types and predicting concentration at a given elevation.

4. Concentration decreases with wave height in the range 50 to 150 cm for spilling and plunging waves, but the relationship for waves less than 50 cm is not adequately resolved.

5. In spilling waves, concentration rapidly increases inside the breakpoint, then remains relatively constant under the bore as it propagates toward the beach. In plunging waves, concentration peaks within a few meters of the breakpoint, then decreases gradually toward shore.

ACKNOWLEDGEMENTS

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