CHAPTER 47

MODE AND PERIOD OF SAND TRANSPORT IN THE SURF ZONE

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ABSTRACT

   Three almometers-water opacity measuring devices-emplaced
perpendicular to the beach,measure instantaneously and continu-
ously the sediment concentration across the surf zone. Most of the
variance of the sand movement is centered in frequencies of less
than 0.25 Hz and between 1.15 and 1.25 Hz. Modes and frequency
of sand transport differ within each of the dynamic zones of the
surf. The motion of sediment in the inner and outer surf zones
is small and virtually independent of the deep water wave periods.
Outside the breaker zone, bed load movement is somewhat coincident
with the prevailing swell period. Lighter concentrations move pre-
dominantly with a 0.8-0.9 second periodicity. In the breaker zone,
sand moves along the bottom with frequencies equal to that of both
the swell and sea, but most of the power is in lower frequencies.
In the breaker zone sand is rarely thrown into suspension. In the
transition zone, sediment motion is largely by suspension with a
period a little longer than the swell.

INTRODUCTION

   Measurement of water opacity and therefore particulate concen-
tration have been made for quite some time. Shelford and Gail (1922)
seem to have been the first to use various light emitting sources
opposite a photo-cell in the field. Since then, many others, among
them, Jakuschoff (1932), Petterson (1934), U.S. Interagency on
Water Resources (1963), Homma and others (1965) and those mentioned
by Das (1972) have used this principle. Longinov (1968) was the
first to use photocells to measure suspended sediment concentra-
tion in the nearshore zone. Most of the instruments, used by these
researchers, measure sediment concentration at a given point per
unit time. The almometer (Brenninkmeyer, 1973, in press) can
measure,at 1cm intervals, from 10 to 500 grams of sediment per
liter of water in the bottom 1.2 meters of water simultaneously
and continuously. This is achieved by placing a vertical series
of 64 photo-electric cells opposite a high intensity flourescent
lamp (Figure 1). The two parts are encased in separate water
tight acrylic cylinders and attached to metal poles which are
anchored in the substrate up to a meter apart. This separation
allows an unimpeded sediment and water flow between the cylinders.
The voltage change of each of the photo cells, as more or less
sediment passes in front of them, is sampled up to every one
fifth of a second, multiplexed and recorded on magnetic tape.

   Three almometers were partially buried in a line perpendicu-
lar to shore on the beach at Point Mugu, California. This area,
located 95 km northwest of Los Angeles, trends N 50 W and is

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Figure 1. The almometer emplaced on the beach. The device con-
sists of two acrylic cylinders; in one is a flourescent lamp
in the other, 64 photo-electric cells.

influenced by a western swell which, during the two week test,
was 75 to 90 cm in height with a 13-16 second period. Almost
half the time the local wind waves were less than 30 cm high
with a 4-8 second period. They also came from the west. The
tides are mixed, with a predominant semidiurnal component.
The tides have a mean range of 1 m and an extreme range of
2.8 m. The sand on the foreshore has a mean diameter of 0.16mm.

SAND MOVEMENT IN THE SURF ZONE

    The three almometers were emplaced, one on the shoreface
(15 cm below MLLW), the second in the lower beachface (30 cm

above MLLW) and the third on the upper beachface (90 cm above
MLLW) so that as the tide, rose and fell, each of the dynamic
zones of the surf regime could be sampled. Only infrequently
can the sediment movement caused by a single wave be detected
with certainty across all three stations. Figure 2 is a typical
example. Since the tide at the time depicted, was 1 m high, the
shoreface (1) is under the breaker zone, the lower beachface
(2) is in the middle surf zone and the upper beachface (3) is
in the transition zone (Schiffman, 1965), the area where the
leading edge of the surf plows into the backwash. Noteworthy
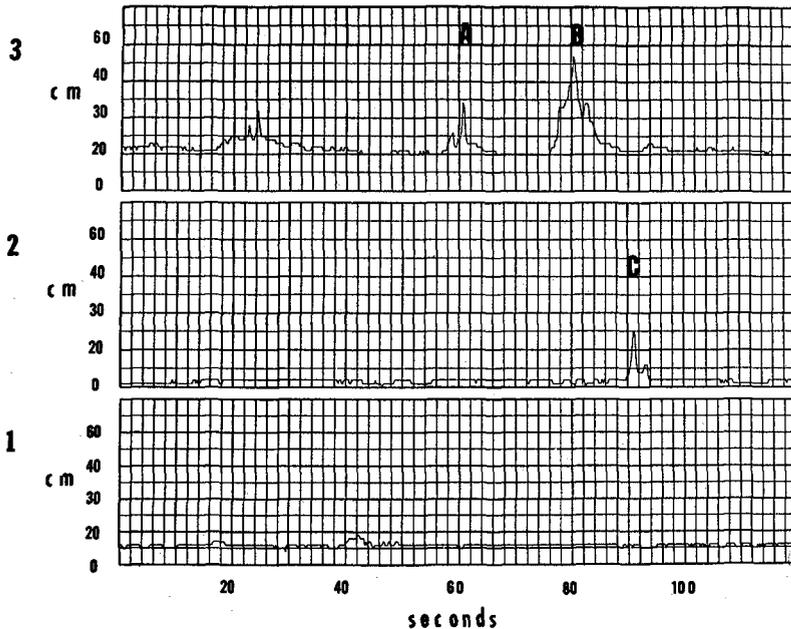

Figure 2 Time rate of change across the surf zone in the
elevation of the sediment concentration of 135 grams per
liter. 1) Breaker zone 2) Middle surf zone 3) Transition
zone.

is the relatively little movement of sand in the breaker zone
and the great agitation in the transition zone. A and B probably
represent an incoming bore and its backwash. As Emery and Gale
(1951) have pointed out, the swash period is considerably longer
than the wave period, which at this time was 13 seconds. After
the incoming swash passed, no deposition had taken place. Where-
as, after the backwash 1 cm had been deposited. During or after
more than half the backwashes deposition takes place.

The only real movement in the middle surf zone (2) was due
to the backwash from B to C. The spacing of the two stations
was 32 m so that the backwash velocity responsible for these
sand uplifts was 2.3 m per second. Either this velocity was not
sufficient to keep the sand in suspension or, more likely, another
surge coming in overtopped the backwash and entrained the top of
the backwash back towards the beach. In either case the suspension
cloud diminished in elevation from 26 to 21 cm above the bottom.

TIME SERIES ANALYSIS

In order to determine the frequency of sediment movement a
spectral analysis was performed on sets of 6000 data points
covering a 20 minute period. The spectra manifest four diverse
forms. In the most common, the great majority of the power is
in the low frequencies,less than 0.1 Hz (Figure 3A). Sometimes,
these peaks are coincident with the swell period but more usually
they are longer than half a minute. Much less common are the
spectra where the preponderance of the power is in the higher
frequencies (Figure 3B) with periods of less than a second. Often
the variance is split between these ranges Figure 3C. When this
occurs there is a peak in the 0.15-0.25 Hz band. Here the peak
is centered on 4.5 seconds. In between from 0.25 to 1.15 and
especially beyond 1.25 Hz there is little power in any frequency.
Only rarely does the spectra display a Dirac delta or impulse
function (Figure 3D) if the station is under water. This form
is to be expected only when a station is above the swash line.
Yet a comparison of parts A and D in Figure 3, taken from the
same station and the same time, but depicting different concen-
trations, shows that right inside the breaker zone there is
little movement of the bottom while considerable quantities of
sand, in a 70 gram per liter slurry, are moved with a periodicity
greater than 13 seconds.

The frequencies in the 1.1-1.3 Hz band may or may not be
present depending on the concentration under consideration.
Figure 3C, 3E and 3F show three different concentrations for
the same station located in the inner surf zone. The 0.81 and
0.86 second periods are absent from the 70 gram per liter con-
centration while they are present in the 40 and 375 gram per
liter densities. The only time that these periods are of paramount
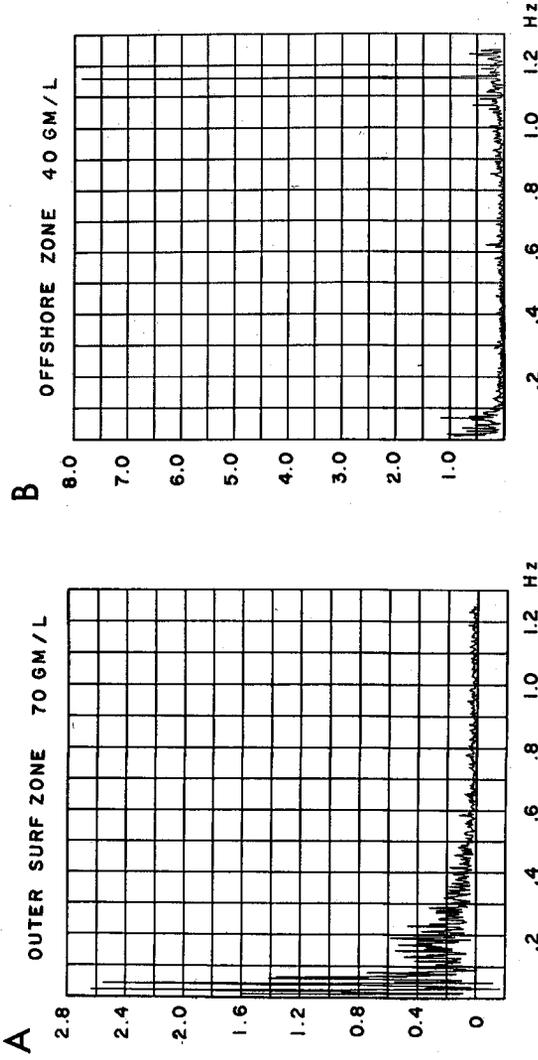
Figure 3   Diverse forms of the power spectra of sediment movement in the surf zone. Part A, all the power is in the lower frequencies. Part B most of the power is in the high frequencies.
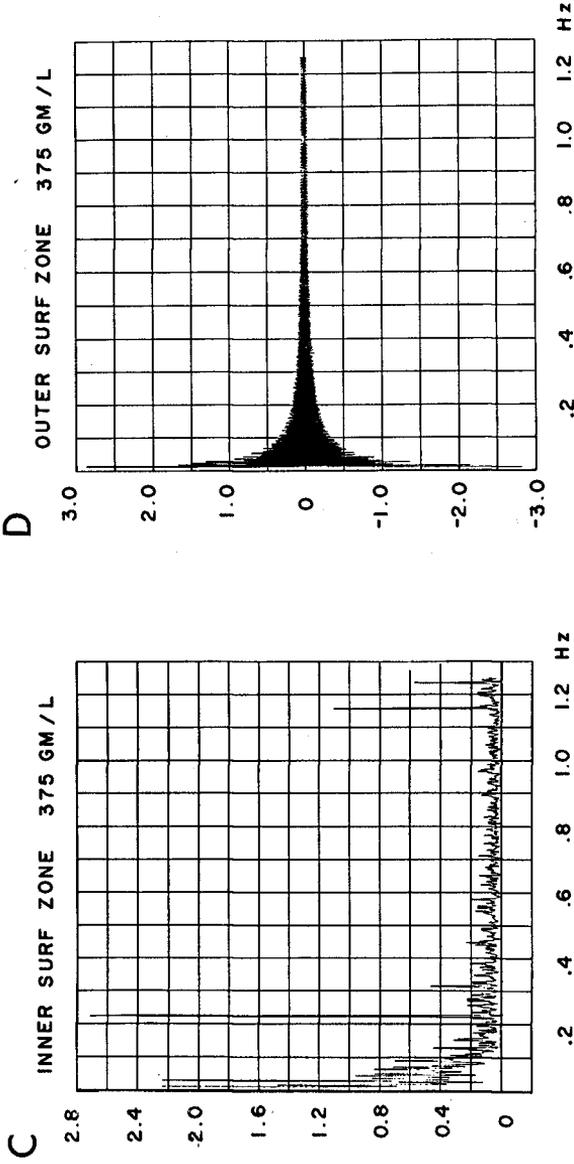
Figure 3 Part C most of the power of the spectrum is in .22 Hz band. Part D only infrequently does an impulse function or no movement of sand occur while the area is under water.
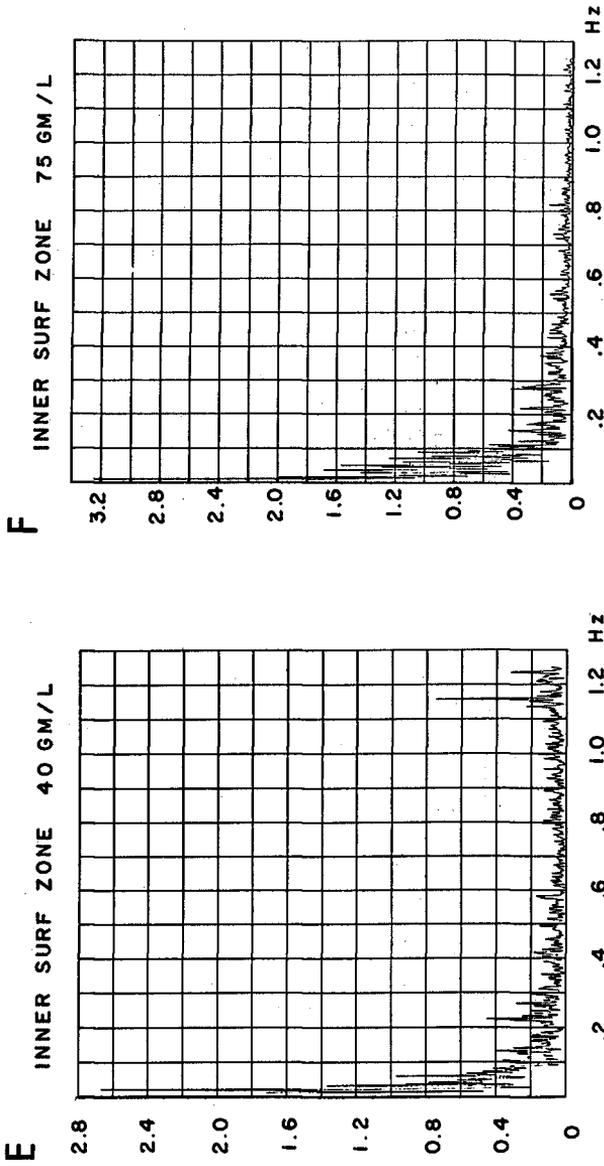
Figure 3 Part E.   In the inner surf zone the 40 gm/l concentration changes elevation with a periodicity of greater than 16 seconds and 0.81 and 0.86 seconds. Part F. The latter periods are absent in the 70 gm/l concentration.

importance is in the lighter concentrations outside the breaker
zone (as in Figure 3(B) where they may be the only frequencies
present. Their significance is somewhat mystifying. They probably
represent smaller movements superimposed on longer period steady
drift. Yet everytime that a short periodicity occurs anywhere in
the nearshore zone it is in this 0.8-0.9 second band. For short
period movements one would expect a range of frequencies. But this
is not the case. They may well be the fundamental mode of short
term sand movement in response to the local turbulent component
of the water which exist up to 1.5 Hz (Huntley and Bowen, 1974).

An enlargement of the lower frequencies, representative of
the response of sediment to deep water waves in the different
areas of the nearshore environment, is shown in Figure 4. Note
that the power of sediment movement in cm^2 has been multiplied
by 10. The power of the waves is in ft^2. Even with this tenfold
increase in the power of the sediment movement, it seldom attains
that of the deep water waves. In each set, the coherency between
the waves and sediment is extremely low (0-0.2) in the middle and
higher frequencies. It improves somewhat (0.2-0.4) for the lower
frequencies, shown here, for the 375 gm/l concentration in the
breaker zone and outside the breaker zone, and for all the con-
centrations in the transition and swash zones.

Outside the breaker zone only the heaviest concentrations,
moving near the bottom, are somewhat influenced by the swell
waves, whereas the lighter concentrations are caught up in the
turbulence and have little response to the longer period sea or
swell. Inside the breaker zone the sediment have a periodicity
of movement that equals that of the swell and also the local sea.
The lighter concentrations lag somewhat behind the predominant
swell period and are less effected by the sea. Yet their main
period of movement is much longer than either the sea or swell.
So that in one area within the breaker zone, not every wave
causes sand motion. This is perhaps, not valid for the entire
breaker zone. The position of the plunge point is not constant,
especially over a 20 minute time span and some of the breakers
may have dissipated their energy before reaching the station
or after passing it.

In the surf zone sediment movement is either non existant,
spread out over many intermediate frequencies, each of which
has relatively low amplitude, or moves only infrequently, less
than once every 30 seconds. It appears, therefore, that sediment
movement, in this zone, is virtually independent of the deep
water wave periods. Dependency has to be sought in reflection,
or other sources of energy such as edge waves, or the inter-
action between successive bores. Also the backwash may still be
effective in this zone. There is a progressive increase sea-
wards in the period of the bed load movement. This lengthening
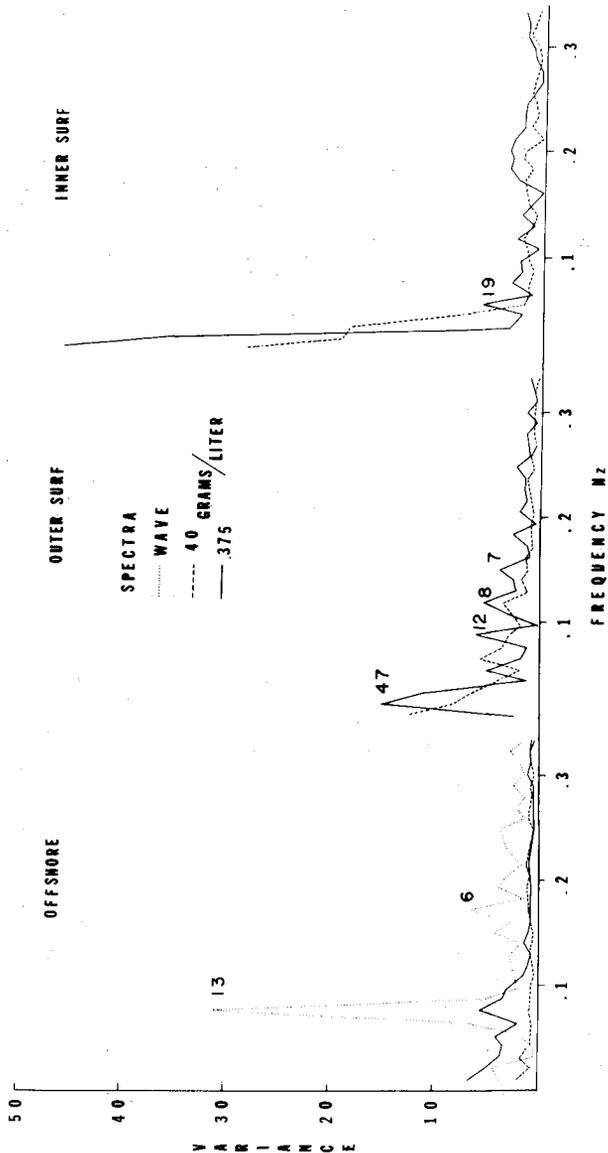of the period seems to die out in the outer surf zone.

Figure 4 Wave and 40 and 375 gram per liter spectra power for the offshore and
outer and inner surf zones. The sand spectra has been multiplied by a factor of
ten. High tide. Wave height 90 cm approaching land at a 20° angle. Wave spectrum
courtesy of the U.S. Army Corps of Engineers, Coastal Engineering Research Center.
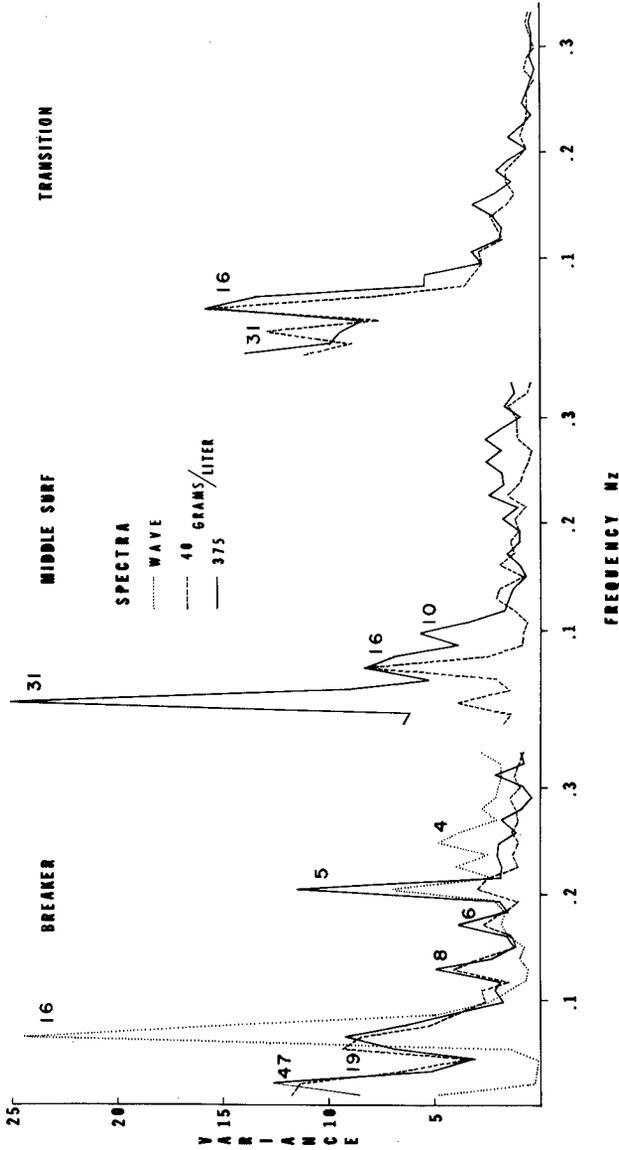
Figure 4B Wave and 40 and 375 gram per liter spectra for the breaker, middle surf and transition zones. The sand spectra power has been multiplied by a factor of ten. Flood tide. Wave height 75 cm, approaching land at a 20° angle. Wave spectrum courtesy of the U.S. Army Corps of Engineers, Coastal Engineering Research Center.
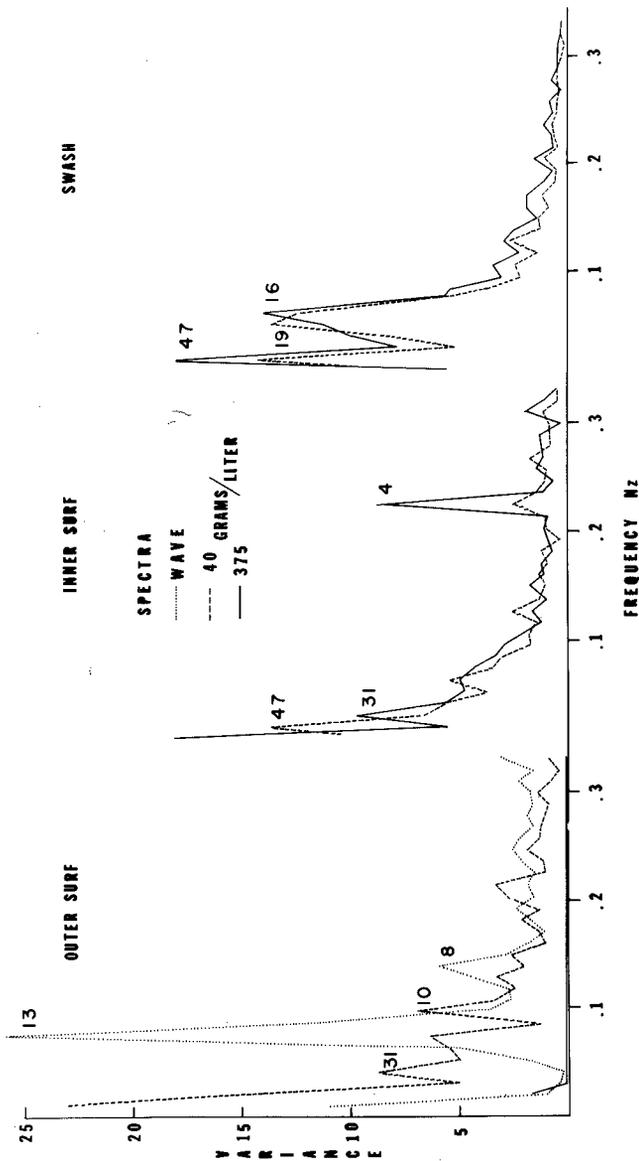
Figure 4C Wave and 40 and 375 gram per liter spectra for the outer and inner surf and swash zones. The sand spectra power has been multiplied by a factor of ten. Beginning of flood tide. Wave height 75 cm approaching land at 5°. Wave spectrum courtesy of U.S. Army of Engineers, Coastal Engineering Research Center.

In the transition and swash zones, the main swell period re-
appears in both concentrations with a lag of up to 3 seconds.
This undoubtedly, represents the retardation of the incoming
bore and coincident with that, the backwash period. The presence
of the local waves is barely detectible since these have diss-
ipated their relatively low energy prior to reaching the station
in interference with the backwash from the swell.

SEDIMENT DENSITY DISTRIBUTIONS

The density distribution of the sediment in the water column
of the surf zone also varies with the dynamic zone. Suspension
of sediment occurs in clouds of short duration. Suspension of
sediment is defined, herein, as any sediment concentration reach-
ing an elevation greater than 15 cm above the bottom. This limit
is the demarcation line between frequent and occasional occurences.
In the 9 tidal cycles studies, 1213 times did the 150 gm/l con-
centration reach this elevation. Only once did sand of 500 gm/l
density reach 1 m above the bottom. The lighter concentrations
usually mimic each other in space and time rather closely. The
heavier concentrations follow a much more subdued path and show
reversals in elevation not experienced by the lighter concen-
trations,(Figure 5). Nor, in every instance, are the heavy con-
centrations effected when the lighter concentrations are raised
above the bottom. Over 87% of these sand fountains (Zenkovich,
 1967) occur when the still water level is within 30 cm above
or below the bottom elevation at the station, ie. in the trans-
ition zone. More than twice as many of the fountains occur on
the flood tide at the beachface station as compared to the ebb.
Part of an explanation may be that the upper beachface is above
the ground water level on the flood tide, whereas on the ebb tide
it is below the ground water table (Emery and Foster, 1948, Fausak,
1970). Below the ground water table there is a surface tension
combined with a probable decrease in the sand roughness coeff-
icient making it more difficult for the sand to be suspended.

The sand uplifts range in duration from only half a second to
53 seconds, averaging 10.2 seconds. Their duration is dependent
on water velocity. In the breaker zone, the sand fountains last
an average of 5 seconds before they are carried out of the measure-
ment field of the almometer. In the transition zone, when that is
located on the lower beachface where it is relatively flat (1:50),
the sand fountains remain for 15 seconds; on the upper beachface,
where it is steeper (1:25), their duration is 11 seconds. On the
ebb tide the fountains last somewhat longer than on the flood
tide.

The water level is insignificant in effecting the heights
attained by the suspension clouds. They average 24 cm in height
even if the still water level is over a meter and a half above
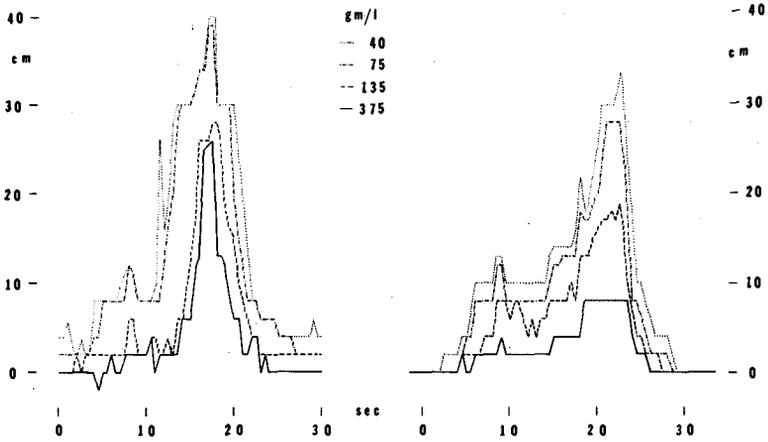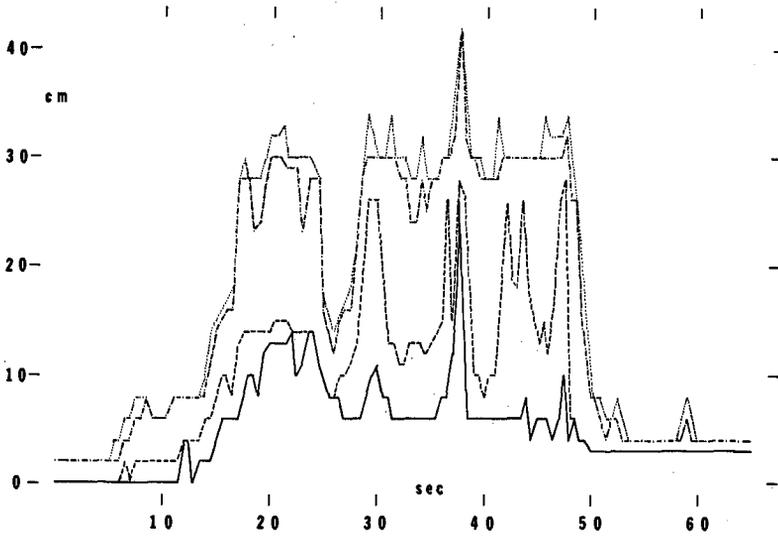the bottom.

Figure 5   Fluctuations in elevation of various concentrations of sand within suspension clouds at the still water level

The average time between the sand fountains on the flood tide
at the upper beachface is 1.7 minutes when the still water level
is 0-30 cm below the station and 2.6 minutes when it is 0-30 cm
above it. During the same tidal stages on the ebb tide, the average
is 3.3 and 5.0 minutes respectively. Plotting the actual times
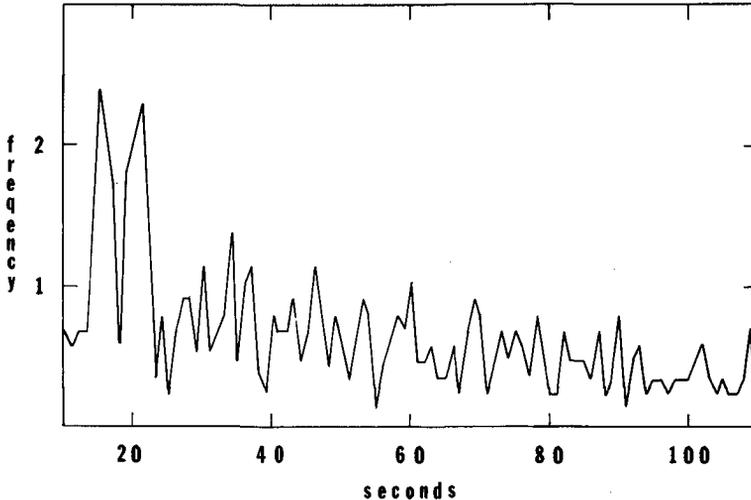between occurences (Figure 6) show that only two small peaks stand

Figure 6   Frequency of occurence of sand fountains on the upper
beachface.

out amidst all the scatter. The 15 second peak represent a 2 second
retardation of the average swell period during the test, the
second peak should be the corresponding backwash period.

There are various causes for the suspension of the sand in this
zone. Measurements of the water velocities inside the surf zone
(Longinov, 1961) show that the maximum vertical components occur
right after the horizontal maximum or when the horizontal compo-
nent is zero;when the water is changing from shoreward movement
to seaward. Suspension in the latter case can occur when the
backwash has a velocity greater than $(gh)1/2$ so that the incoming
bore cannot progress against it, resulting in a hydraulic jump
or roll wave. At an average backwash velocity of 180 cm/sec
(Dolan, Ferm and McArthur, 1969) the water depth at which the
Froude number becomes critical is just under 30 cm. In the breaking
of this roll wave there is a brief suspension of much sediment.

Then the water movement eally stops and most of the suspendeds
fall back to the bottom. The deposits of these suspendeds may
well form the steep sided symmetrical ripples so common in the
transition zone on steep beaches (Clifton and others, 1971).
These ripples, on their own, may cause more suspension by creating
a barrier to the backwash flow and again setting up a hydraulic
jump.

   Also, at the inner breaker line, the wave front is saturated
with air bubbles which penetrate the bottom. The ascent of these
bubbles have a suctional effect sufficient to draw up sand
(Aibulatov, 1966).

   Only four percent of the suspension clouds occur in the breaker
zone. The sand surface changes often, with differences in elevation
of the bottom of more than 6 cm per wave not uncommon. But great
quantities of sand are rarely thrown into suspension. This dearth
of sand fountains near the primary breaker suggests that the water
and the air entrapped in the breaker does not reach the bottom but
is absorbed in the water layers above it.

CONCLUSIONS

   Measurements of changes in elevation of different sand concen-
trations within the surf zone have shown that diverse responses
to the incoming waves are operative in each of the dynamic zones.
Most of the sediment movement within each of these zones occurs
with a periodicity two to three times longer than that of the
incoming waves. Just outside the breaker zone, when sediment does
move, the bed load is transported in pulses coincident with the
prevailing swell period. A much shorter periodicity prevails
in the lighter concentrations. Inside the breaker zone, sand moves
with frequencies equal to both the swell and sea periods. The sand
surface changes rapidly with differences in elevation of more
than six centimeters per wave not uncommon. Here sand is rarely
thrown into suspension. After the transformation of the wave into
a bore in the outer surf zone, sediment movement is absent or
small and therefore almost independent of the deep water wave
periods. In the inner surf zone, suspended sediment transport
increases in frequency, elevation and duration. In the transition
zone sand movement by suspension becomes predominant. Upheavals
of the sand are common and show a variety of different shapes
in response to secondary breakers penetrating the bottom or hy-
draulic jumps. The frequency of movement reflects the predominant
swell and backwash period with a lag of up to three seconds.

ACKNOWLEDGEMENTS

REFERENCES

Aibulatov, N.A., 1966, Investigations of longshore migration
        of sand in the sea: Moscow Nauka Publ., 159p. (In Russian)
Brenninkmeyer, B.M., 1973, Synoptic surf zone sedimentation
        patterns: Unpl. dissertation, Univ. of Southern California,
        274 p.
-----,in press, In situ measurement of rapidly changing high
        sediment concentrations: Marine Geology.
Clifton, H.E., Hunter, R.E., and Phillips, R.L., 1971, Depositional
        structures and processes in the non-barred high-energy near-
        shore: Jour. Sed. Petrology, v.41, p. 651-670.
Das, M.M., 1972, Suspended sediment and longshore transport data
        review: Thirteenth Conf. on Coastal Engineering, p. 1027-1048.
Dolan, R., Ferm, J.C. and McArthur, D., 1969, Measurements of
        beach process variables, Outer Banks, North Carolina:
        Louisiana State Univ., Coastal Studies Inst., Tech. Rept.,
        64, 79p.
Emery, K.O. and Foster, J.F., 1948, Water table in marine beaches:
        Jour. Marine Research, v.3, p.644-654.
-----,and Gale, J.F.,Swash and swash marks: Am. Geophys. Trans.,
        v. 32, p.31-36.
Fausak, L.E., 1970, The beach water table as a response variable
        of the beach-ocean-atmosphere system: Unpl. thesis Virginia
        Inst. Marine Science, 52p.
Homma, M., Horikawa, K. and Kajima, R., 1965, A study of suspended
        sediment due to wave action: Coastal Engineering in Japan,
        v.3, p.101-122.
Huntley,D.A. and Bowen, A.J., 1974, Field measurements of nearshore
        velocities: fourteenth conf. on Coastal Engineering.
Jakuschoff, P., 1932, Schwebestoffbewegung in Flussen in Theorie
        und Praxis: Inst. fur Wasserbau der Technischen Hochschule
        Berlin, Mitteil., 10, 24p.
Longinov, V.V., 1961, The determination of maximum wave velocities
        in the shore zone of the sea: Akad. Nauk SSSR Inst. Okeanol.
        Trudy, v48, p.287-308 (in Russian)
-----,1968, Determination by a photoelectric method of sand suspen-
        sion concentration in the littoral zone during waves:
        Gosudarstvennyi proektno-konstruktorskii i Naucho-issledovatel'
        skii Institut Morskogo Transporta (Leningrad) v.20/26, p.
        89-92 (in Russian).
Schiffman, A., 1965, Energy measurements of the swash-surf system:
        Limnology and Oceanography, v.10, p.255-260.
Shelford, V.E. and Gail, F.W., 1922, A study of light penetration
        into sea water made with the Kunz photoelectric cell with
        particular reference to the distribution of plants: Puget
        Sound Biol. Station Pub. v.3, p.141-176.
U.S. Interagency Committee on Water Resources, 1963, Measurements
        and analysis of sediment loads in streams:Rept 14, 151p.
Zenkovich, V.P., 1967, Processes of coastal development: New York,
        Interscience, 738p.