A FIELD INVESTIGATION OF SAND TRANSPORT IN THE SURF ZONE

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ABSTRACT

The distribution of bed-load sand transport normal to the beach has been measured in a series of field experiments conducted in the surf zone at Fernandina Beach, Florida. Simultaneous measurements were made of the waves and water particle motion at various locations in the surf zone. The energy flux of the waves was resolved into its longshore component from the measured directional and energy spectra. It is found that the bed-load transport is related to the depth of water and longshore energy flux. Insight into the mechanics of sediment transport is obtained by comparing the wave and water particle motion energy spectra, which give a direct measure of the kinetic and potential energy, at various locations in the surf zone.

INTRODUCTION

A meaningful field investigation of the sand transport processes in the surf zone requires the synoptic measurement of a number of hydrodynamic and sediment variables. Fairly complete and extensive data are required to evaluate the validity of various proposed sand transport relationships and the formulations of new relationships where necessary.

This paper describes field experiments conducted in the surf zone at Fernandina Beach, located on the northeastern coast of Florida. The emphasis of this study was to obtain information concerning the distribution of bed-load transport perpendicular to shore and the physical processes causing such movement. Sediment transport in the surf zone can be considered as being caused by a combination of shear stresses due to wave and current action. An attempt to correlate sediment transport with physical parameters then must include good wave and current measurements.

The experiments were conducted from October, 1966 to May, 1967, a period that encompasses the more intense wave activity along this coast. The beach and nearshore bottom profile is typically a one or two bar system with a gentle slope of two to three per cent. The sand has a mean grain size of approximately 0.2 millimeters. The mean tidal range is 1.7 meters.

The physical parameters measured during the experiments were the time history of the wave height, wave direction, instantaneous water particle velocities, tides, wind direction and speed, quantity of sediment transport, bottom contour profiles, and sediment characteristics.

The measurements were conducted from a pier traversing the surf zone seaward to the outer bar, that is to the first breaker line. A plan of the pier and location of the instrumentation is shown in Figure 1. A typical bottom profile taken adjacent to the pier is also shown in this figure. During the course of the experiments the waves "peaked" or spilled on the outer bar, crossed the bar, and carried on into the inner bar where they broke. The experiments were limited to the study of the bed-load transport in the area bounded by the outer and inner bar.

Since this is not the area of intense turbulence, the mode of transport is primarily due to bed-load which includes saltation. It should be pointed out that this area represents only a portion of the surf zone, and the quantity of sand measured was not the total littoral drift, but represents a significant contribution to the total.

EXPERIMENT

The experiments were conducted over approximately half a tidal cycle, usually four to six hours. The tide recorder, anemometer, and sand traps operated continuously during the experiment. Current measurements were taken at various locations for durations of at least five minutes and up to twenty minutes. Waves were measured simultaneously and at the same location as the current measurements. Also during the test, wave measurements at two locations at the end of the pier were taken simultaneously for a period of twenty minutes. The instrumentation and details of measurements are described below.

Taking measurements in the surf zone is very difficult due to the tremendous forces exerted by the waves. It is almost essential for synoptic measurements to have a stable platform from which to work. This platform, a fishing pier in this case, exerts some local influence on the environment being measured and care must be taken to minimize this effect. Thus, all measurements were made as far from the pier and its piling as possible, and the measurements were taken on the updrift side of the pier on which the incident waves impinge first.

A pier or similar structure extending out from the beach can also exert an influence on the general circulation patterns of the surf zone. The pier can act as a perturbation on the longshore current system, and one often observes a rip current generated near the tip of such structures. Care was taken to note the occurrence of rip currents being generated at the pier, and such occurrences have been treated as being anamolous. Data taken during such experiments have been excluded.

Another effect of the pier was noted from the bathymetry of the area adjacent to the pier. It is found that there was considerable scour about the seaward end of the pier which certainly influences the sediment transport

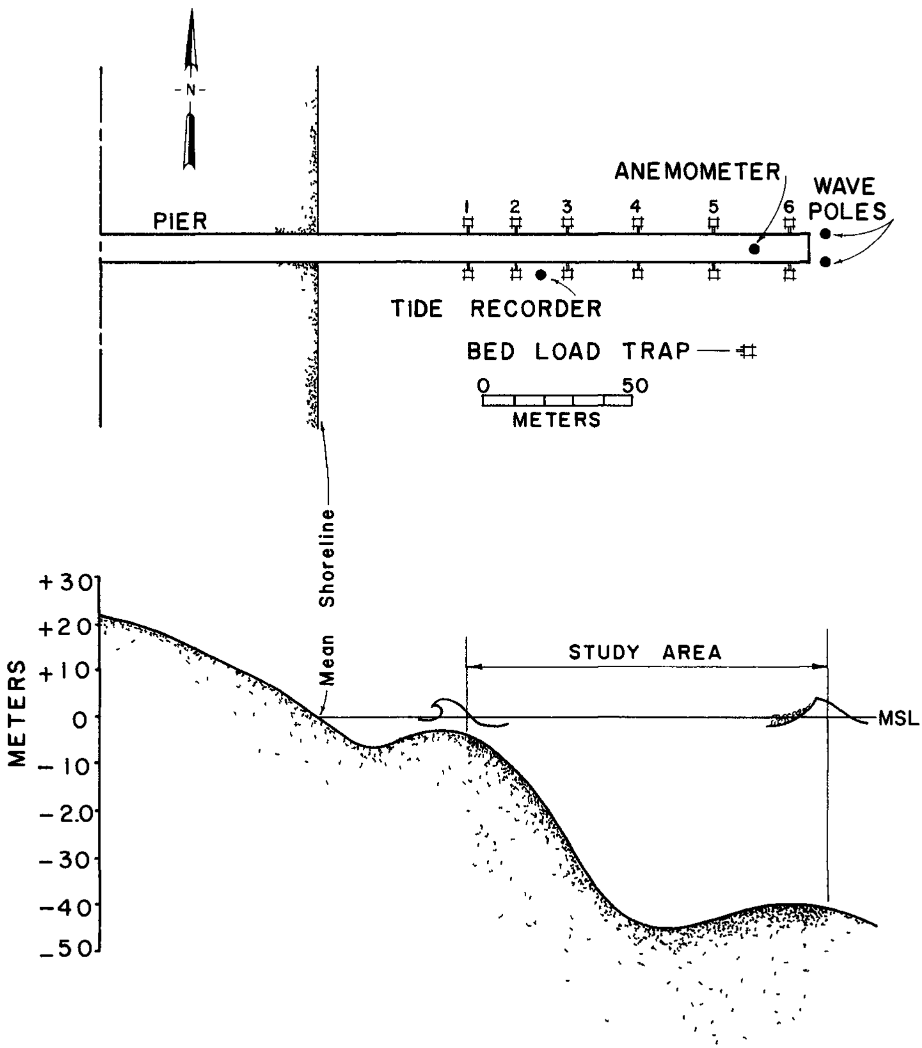

FIGURE I. INSTRUMENTATION AND BOTTOM PROFILE AT FERNANDINA BEACH PIER in this vicinity. Similar scour about the ends of other piers has also been found elsewhere. It was also noted that there was some slight accretion of sand at the shoreward end of the pier in the swash-zone area.

Current measurements

The measuring of accurate current velocities in the presence of a wave field, such as the surf zone, has long been a problem. This has greatly limited the quantitative nature of results collected pertaining to sediment transport in the ocean. An electromagnetic flowmeter was used during these experiments and proved applicable for use in the surf zone. This instrument was used essentially as a turbulence meter. With this instrument, not only the mean, but the fluctuations about the mean, or the turbulent velocities, are measured.

Problems encountered in the surf zone with conventional current meters are due to the suspended sediments and rapid water particle accelerations. The suspended sediments tend to wear out bearings or moving parts. Propeller or rotor-type meters have a poor response to rapid accelerations due to the inertia of the blades. Since the electromagnetic current meter utilizes no moving parts, these problems have been eliminated.

The current meter mounted on a tripod is shown in Figure 2. Its overall length is 15 centimeters with an inside bore diameter of 1 centimeter. Calibration of the instrument showed it to have very linear characteristics over the velocity range of less than 0.03 meter per second to more than 5 meters per second, which was the range of the calibrating facilities. The tests also showed the instrument to have a fairly flat response up to frequencies of one cycle per second. For a complete description of the current meter and other instrumentation the reader is referred to Thornton (1968).

It was found necessary to mount the current meter on a tripod rather than on the pier in order to have the desired rigid mounting. The pier, although a stable platform to work off, responds to the wave motion with a frequency approximately the same as the frequency of the waves. The motion of the pier is mostly lateral. This motion has negligible effect on the wave measurements but introduces a serious impressed motion on the current meter record. The natural frequency of the tripod is much higher than frequencies of interest for the measured water particle velocities and has proven to be an excellent mounting.

Wave measurements

Waves, as they appear in nature, are essentially aperiodic or random in nature and as such have to be treated as a statistical phenomenon. The studies were conducted over a relatively short duration of time, half tidal cycle or less, and, as such the physical environment may be assumed quasi-stationary. Since a stationary system can be assumed, spectral analysis was employed in treating this aperiodic phenomenon.

Both energy-density spectra and directional spectra of the waves were measured by means of two resistance wire wave poles located at the end of the pier. The outer bar delineates the seaward edge of the surf zone, and,

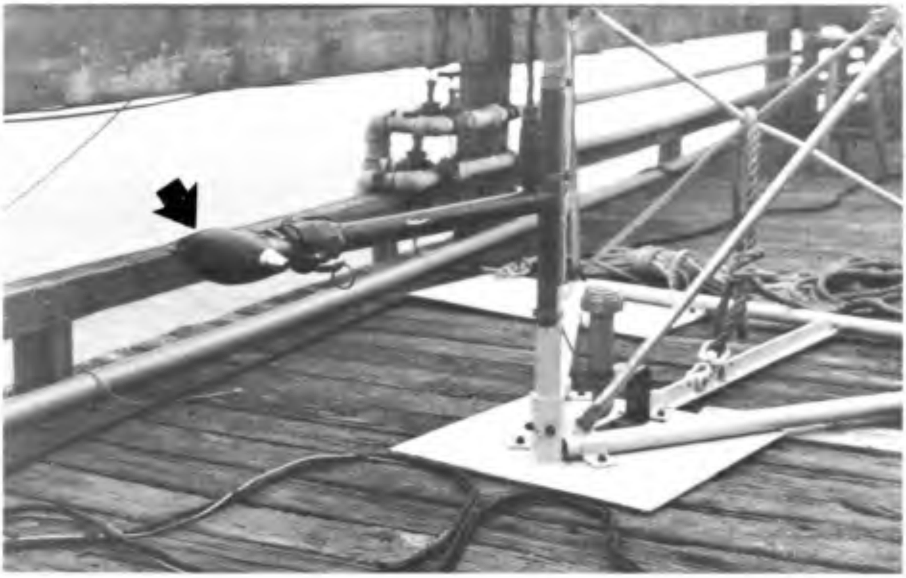

FIGURE 2
ELECTROMAGNETIC FLOW METER

FIGURE 3
BED-LOAD TRAP

since the waves were recorded here, the energy input into the surf zone was measured directly. By computing the Fourier transform of the cross-correlation function of the two wave records, a single directional spectrum is obtained. This analysis associates a direction with each frequency component and is essentially a measure of the phase difference between the two measuring locations for each Fourier component.

A pressure transducer to measure wave heights was mounted on the same tripod as the current meter so that a direct correlation of the water particle velocity and wave height could be obtained at the same location in the surf zone.

Bed-load traps

The quantity of sand transport was measured by means of bed-load traps which are aligned in the direction of the longshore current. These traps, shown in Figure 3, rest on the bottom and sample an area 20 centimeters high by 40 centimeters wide. The bed-load movement here is defined by the height of the traps and, as such, includes saltation. Up to six traps were used simultaneously.

The unique design of these traps has evolved over several years of use, and they have proven to be very rugged and dependable for the severe conditions under which they are subjected. For a more complete description of the traps and attendant system, see P. Bruun and J. Purpura (1964).

Analysis

Meaningful information from the wave and current meter records can be obtained by computing the individual energy-density spectra. A time series record of finite duration, extending from t_1 to t_2 can be represented in the form of a Fourier integral

$$\eta(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} A(\sigma)\, e^{i\sigma t}\, d\sigma \qquad (1)$$

where the $A(\sigma)$ is the complex amplitude spectrum and is a continuous function of the frequency, σ. $A(\sigma)$ can be determined by the Fourier transform of the time series representation of the wave record given by

$$A(\sigma) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \eta(t)\, e^{-i\sigma t}\, dt = |A(\sigma)|\, e^{i\varepsilon} \qquad (2)$$

where ε is the argument, or phase angle, of $A(\sigma)$.

The energy-density spectrum, $\Phi(\sigma)$, is proportional to the square of the modulus of the amplitude spectrum

$$\Phi(\sigma) = |A(\sigma)|^2 \qquad (3)$$

The amplitude spectrum can be determined via either the mean-lagged product as presented in Blackman and Tuckey (1958) or directly by the computationally faster Fast-Fourier-transform method that is outlined in Bingham, et al. (1967).

The potential and kinetic energy of the waves and water particle motion, respectively, can be obtained by integrating the energy-density components over all frequencies where

$$\frac{1}{16}\rho g\overline{H}^2 = \frac{1}{2}\rho g \int_0^\infty |A_H(\sigma)|^2 \, d\sigma = \text{average potential energy of waves/unit area}$$

$$\frac{1}{2}\rho\overline{u}^2 = \frac{1}{2}\rho \int_0^\infty |A_u(\sigma)|^2 \, d\sigma = \text{average kinetic energy of water particle motion/unit volume}$$

A measure of the directional characteristics of the waves can be obtained from the simultaneous time records of the two wave poles at the end of the pier. This method of analysis was suggested to the author by Dr. R. G. Dean and is fully described by Thornton (1968). A single directional spectrum of the waves is obtained by computing the Fourier transform of the cross-correlation function of the two wave records. The analysis associates a direction with each frequency component and is essentially a measure of the phase difference between the two measuring locations for each Fourier component.

Let us consider for the moment monochromatic waves having an infinitely long-wave train approaching under asimuth β, with amplitude a, frequency $\sigma = 2\pi/T$, and wave number $k = 2\pi/L$, where T and L are wave period and length, respectively. We will assume the frequency and wave number can be related with sufficient accuracy by the small amplitude wave theory relation

$$\sigma^2 = gk \tanh kh$$

The wave displacement is represented as

$$\eta(x,y,t) = A(\sigma)\, e^{(\sigma t - k\cos\beta\cdot x - k\sin\beta\cdot y - \varepsilon)}$$

Using a coordinate system (x,y) with the origin at the reference wave sensor (1) and the x-axis through the secondary wave sensor (2) (see Fig. 7), the measured water surface displacement due to this single component can be represented in complex notation

$$\eta_1(o,o,t) = |A_1(\sigma)|\ e^{i(\sigma t-\varepsilon_1)} \tag{4a}$$

$$\eta_2(o,s,t) = |A_2(\sigma)|\ e^{i(\sigma t-k\sin\beta\cdot s-\varepsilon_2)} \tag{4b}$$

where s is the separation distance between the wave sensors. For monochromatic waves, the phase angles are equal $\varepsilon(\sigma) = \varepsilon_1 = \varepsilon_2$.

The cross-spectrum $\Phi_{12}(\sigma)$ for a particular frequency can be obtained from the complex amplitude spectra of the two individual wave records as computed in Equation (2).

$$\begin{aligned}\Phi_{12}(\sigma) &= C_{12} + iQ_{12} = |\Phi_{12}|\ e^{i\delta} \\ &= |A_1(\sigma)|\ |A_2(\sigma)|\ e^{ik\sin\beta\cdot s}\end{aligned} \tag{5}$$

where C_{12} is the co-spectrum, and Q_{12} is the quadrative spectrum, and

$$|\Phi_{12}| = [C_{12}{}^2 + Q_{12}{}^2]^{\frac{1}{2}} = |A_1(\sigma)|\ |A_2(\sigma)|$$

$$\delta = \tan^{-1}\frac{Q_{12}}{C_{12}}$$

Equating arguments in Equation (5), we find

$$\beta(\sigma) = \sin^{-1}\left[\frac{\delta(\sigma)}{k(\sigma)s}\right] \tag{6}$$

where β is the asimuth of the approaching wave for a particular frequency. Thus, from the record of two wave sensors it is possible to infer a single wave direction for each frequency. The assumed wave system is, therefore, equivalent to an infinite number of wave frequencies composing the spectrum, with the directional characteristics of each component described by a single value.

The separation distance, s, of the wave meters must be short enough so that the criterion of long-crested waves is realized, and it is also required that they be separated by sufficient distance to obtain good resolution. It should be noted that for the case of two sensors, there is a direction ambiguity for each frequency of 180 degrees. In our application, the measurement of waves is close enough to the shore so that, except for possibly very high frequencies which are of minor importance, the direction is uniquely determined. It also should be cautioned that the interpretation of the determined direction for a frequency component with broad directional or multi-directional characteristics would certainly be questionable.

Past sediment transport studies have indicated the longshore component of wave energy flux to be an important parameter in determining the littoral drift. We can easily calculate the total longshore energy flux, P_l, from the information obtained from the energy and directional spectra of the waves. Assuming the linear wave theory approximation for the group velocity of the individual energy components

$$C_G(\sigma) = \frac{\sigma}{2k}\left[1 + \frac{2kh}{\sinh 2kh}\right]$$

and equal partitioning of kinetic and potential energy in the wave, P_ℓ is given by

$$P_\ell = 2 \sum_{0}^{\infty} C_G(\sigma)\ \rho g \Phi(\sigma)\ \sin 2\beta \qquad (7)$$

RESULTS

Insight into the mechanics of sediment transport in the surf zone can be gained by examining the waves and currents. The results of the experiment conducted on May 24, 1967, are used as typical of the results to illustrate the fluid-sediment mechanics of the system measured. The weather on this date was very good with maximum winds of less than eight knots. A predominant swell which was quite regular was from the north quadrant which originated from a distant storm system located off the northeastern part of the United States. The wind and swell conditions were quite constant throughout the test.

The quantity of bed-load sand transport as a function of time is shown in Figure 4. Each point of the curve represents a twenty minute average for the longshore bed-load transport at a particular location in the surf zone. The four curves indicate the sand caught at traps 1 through 4. (See Figure 1 for location of traps.) The tidal curve is represented below to show the changes in the mean water depth during the experiment. The changes in water depth were minimized by working over the peak of the tidal curve.

One of the most striking features of the diagram is the variability of the sand transport with time, even though the waves were quite constant during this time. This is indicative of the very complex nature of the sediment transport problem in the surf zone. Generally, it is noted that the sediment transport is related to the depth, that is, the sand transport increases with decreasing depth.

The results of the spectral analysis of the wave and current records is given in Figures 5-7 showing a comparison of measurements taken at various locations in the surf zone. Generally, it can be seen from the figures that the kinetic energy of the fluid particles increased in a shoreward direction while the potential energy decreased which is indicative of a system dissipating energy. In this case, the waves were "spilling" between the two measuring locations. In an "ideal" wave system (non-dissipative), for which potential theory would be valid, we would expect the potential energy to increase since the energy flux would be constant and the group velocity would be decreasing due to decreasing depth.

A comparison of the energy spectra of the waves at the breaker's edge and at a location 70 meters inshore in Figure 6 shows the potential energy of the waves to be decreasing in a shoreward direction. The shape of the spectra is attributed to the nonlinear character of the waves in the surf zone wherein several harmonics of the fundamental peak can be seen. It will be noticed in the comparison of the two wave spectra that there is a decrease in the fundamental peak of the inshore spectra but an increase in the higher frequency peak. This might indicate the loss in energy in the lower frequencies due to spilling and nonlinear transfer of energy to higher frequencies. The spectra of the water particle velocities demonstrated a similar shift in energy-density to higher frequencies.

Figure 6 shows the measurement of the kinetic energy measured 55 centimeters from the bottom at two locations in the surf zone. It can be seen that there is an increase in the kinetic energy from the offshore station (150 meters) to onshore (120 meters). This can be attributed to the transfer of potential energy to kinetic and turbulent energy in the shoaling and spilling process. The increase in kinetic energy would be indicative of an increase in shear stress at the bottom due to wave and turbulent action. This increase in shear stress would result in more sediment being placed in motion for transport by the longshore current. Assuming a uniform longshore current (the shear stress for the current alone being essentially uniform), one would expect longshore drift to increase in the shoreward direction. This was generally substantiated by the sampling of the bed-load traps.

Also shown in Figure 6 is the kinetic energy spectrum of the parallel to shore component. The energy of this spectrum was approximately one-tenth that of the component aligned with the waves. It should be pointed out that the directional response of an orifice-type current meter is not fully determined for angles of incidence approaching 90 degrees. Therefore, the spectrum of this component should be viewed with reservations although it is felt that the measure of the mean current of 0.23 meters per second is fairly accurate. This spectrum does show relatively more energy content in the low frequencies as one would expect.

The calculated directional spectrum from the two wave sensors is given in Figure 7. From this spectrum and the wave energy spectrum the longshore energy flux can be resolved as given in Equation (7).

An empirical correlation of the wave and sediment transport quantities by dimensionless grouping of the pertinent variables was attempted in order to determine the relative importance of the various parameters. These can be represented in terms of dimensionless parameters in the following functional form

$$\frac{QH_s}{P_\ell} = f(H_s/d) \qquad (8)$$

where

Q = quantity of sand transport (gm/min/m)

H_s = significant wave height (m)

P_ℓ = longshore wave component of energy flux (gm-m^2/sec/m^2)

d = depth of water (m)

The results of these and earlier experiments are summarized in Figure 8. The figure indicates that generally the sand transport increases as the depth decreases. Since a bar-trough profile was usually present, this relationship indicates higher transport rates on the bars than in the troughs. The greater transport of sand on the bar and other shoal areas in comparison with the trough was also demonstrated in earlier experiments using fluorescent tracers.

These results were limited to experiments where the significant wave height at the edge of the surf zone was generally less than one meter. For larger wave heights, the sediment transport data greatly deviated, falling under the curve shown. This may be due to the fact that for higher waves the mode of sand transport is changed; a significant portion of the transport may be due to suspended load and was not measured by the bed-load traps.

The results of these experiments were compared to the littoral drift formula used by the Coastal Engineering Research Center (ref. 5) which relates longshore wave energy flux to total littoral drift. The total bed-load during the tests between the outer and inner bar can be determined approximately by integrating the empirical curve shown in Figure 8 over the limits from deep water to the inner breaker line for a particular set of wave conditions. The comparison of the two relations showed the bed-load measurements to be ten to forty per cent of the total littoral drift as given by the CERC formula. This is within the range of expected values and appears to give good comparison of the two sets of information.

ACKNOWLEDGMENTS

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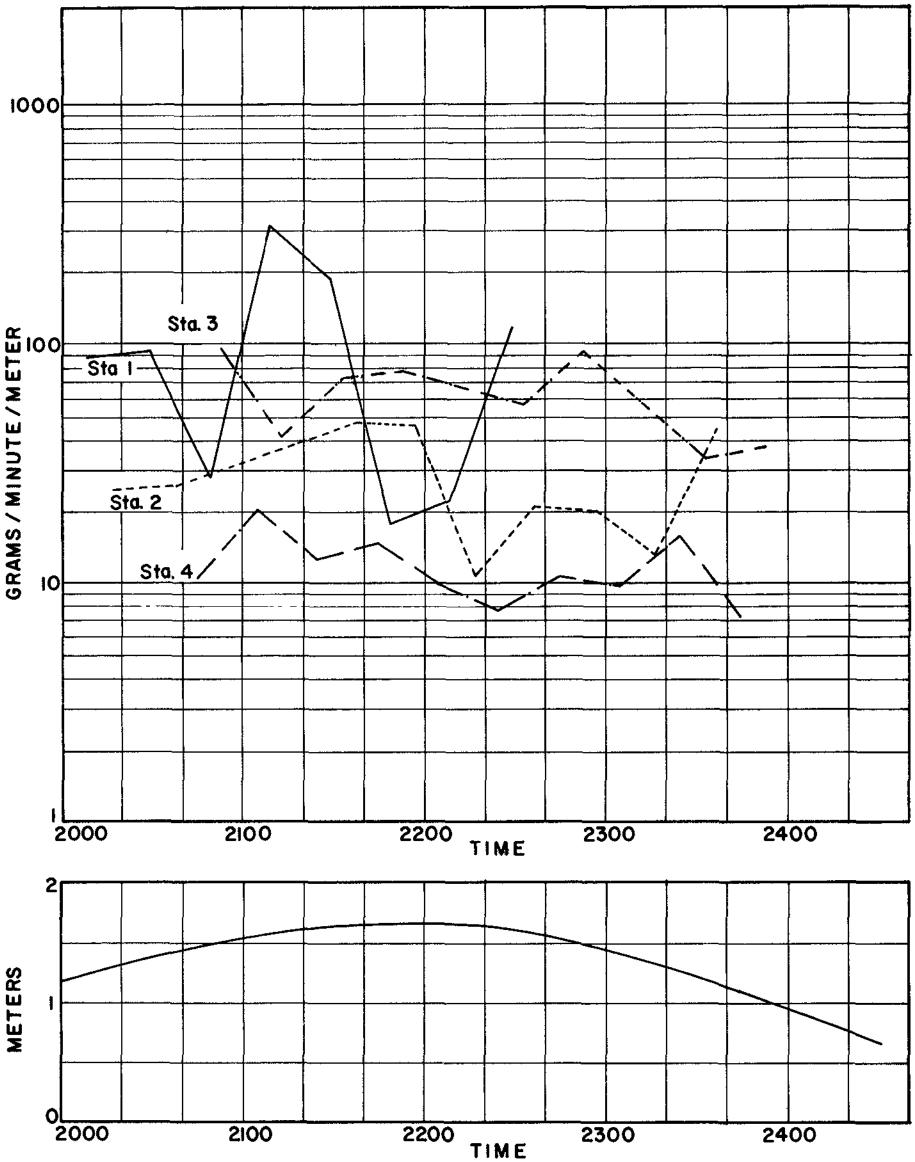

FIGURE 4. SAND TRANSPORT, 24 MAY 1967

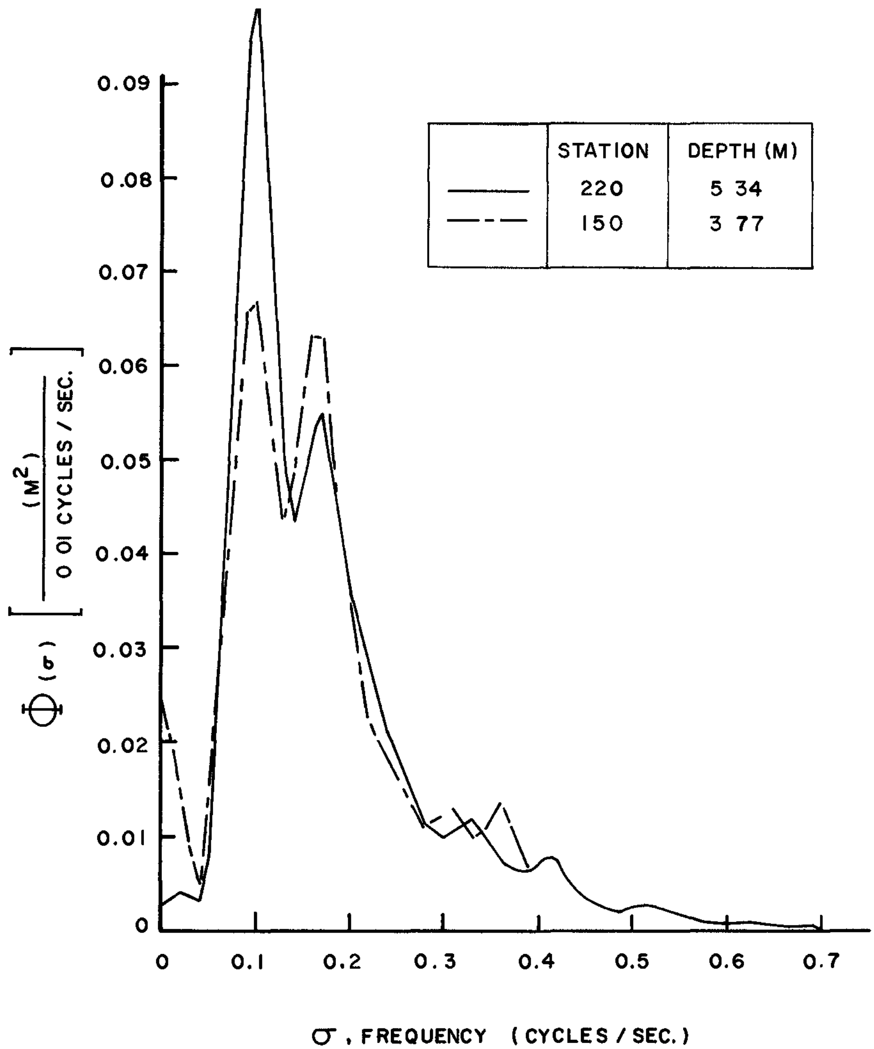

FIGURE 5. WAVE SPECTRA, 24 MAY 1967

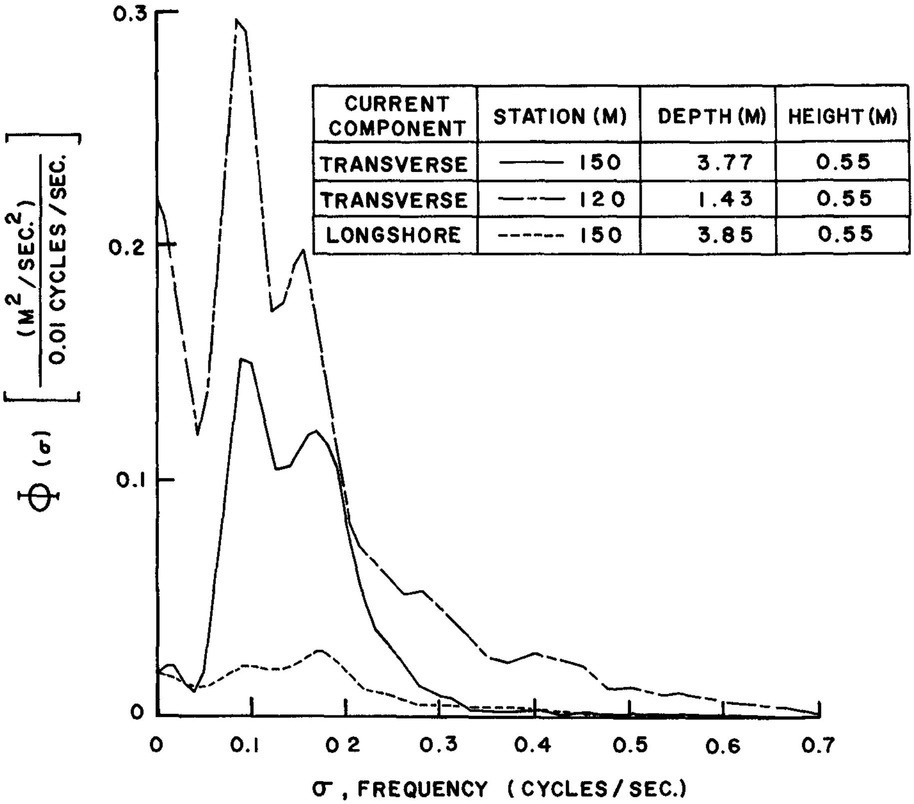

FIGURE 6. WATER PARTICLE VELOCITY SPECTRA
24 MAY 1967

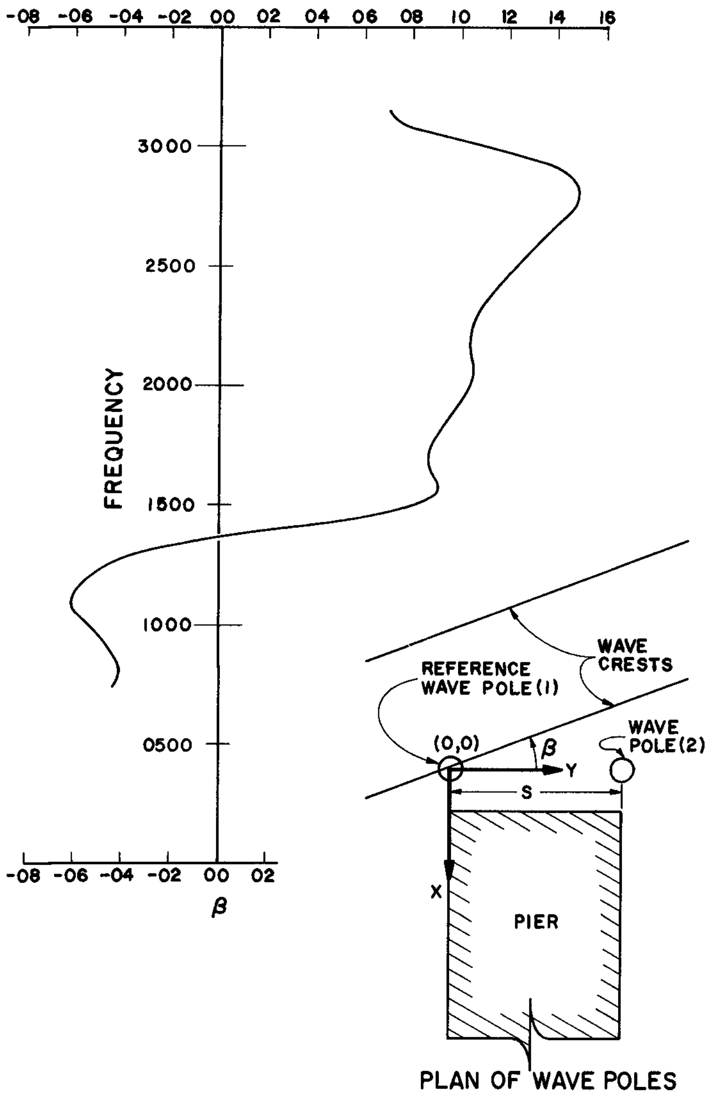

FIGURE 7. DIRECTIONAL SPECTRUM OF WAVES

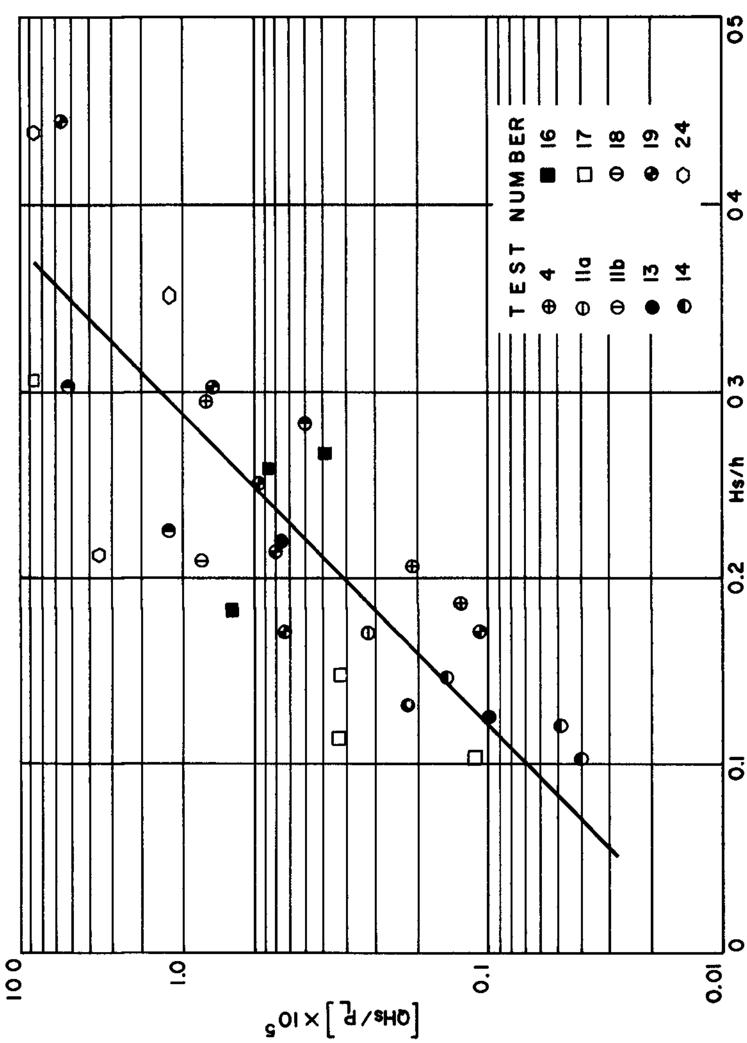

FIGURE 8. CORRELATION OF SEDIMENT, LONGSHORE WAVE POWER, AND DEPTH