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# The Influence of Energy Grouping and Undulation on Sediment Suspension in the Surf Zone

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## The Influence of Energy Grouping and Undulation on Sediment Suspension in the Surf Zone

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# THE INFLUENCE OF ENERGY GROUPING AND UNDULATING ON SEDIMENT SUSPENSION IN THE SURF ZONE

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Key words: wave energy grouping and undulating, suspended sediment, IMF analysis.

## ABSTRACT

A field experiment was conducted to investigate the effects of the wave energy grouping and undulating on the sediment suspension in the surf zone at Taichung, Taiwan, in 1995. Instruments were deployed in line with the wave front, including one acoustic current meter, one pressure sensor, and four optical turbidity monitors were arranged in line and perpendicular to the bed. During the experiments the water depth was varied from 0.7 m to 3.6 m due to the tide level variations. The instruments were fixed to the ground to have data collected throughout the surf zone while the relative position of the station in the surf zone was varied with the tide level. Sediment suspension events associated with the group wave motions reached peak concentrations were 2-3 times larger than that associated with waves without grouping. A new approach using Hilbert transform and Intrinsic Mode Functions (IMF) analysis to explore the effect of energy grouping and undulating on sediment suspension is presented. It gives a close insight to the suspended sediment distribution and wave characteristics in the surf zone. An interesting bursting phenomenon of bed concentration was found dominating in the surf zone, which was closely related to the incident wave groups.

## INTRODUCTION

Characteristics of grouped waves propagating in the surf zone are important for both longshore sediment transport and shoreline changes. However only a few field data are made clear because of the difficulty of the observation [10,15]. Real sea waves can result in a notable wave grouping state even in the open seas [16]. As those wave groups propagate toward the beach, their shapes and structures are transformed due to a combination of shoaling and breaking effects. Such transformations of wave groups have important practical consequences, since it directly affects the distribution of suspended sediments.

Grouped waves in the surf zone are usually accompanied by low frequency motions [14]. It has been suggested that low frequency motions are related to the suspended sediment transport in the surf zone [1,3]. The interaction between wave grouping and the bursting phenomenon of sediment suspension, however, is not clear and the studies of sediment transport are still confined in the individual wave actions.

## STUDY AREAS AND METHODOLOGY

Field experiments were conducted at Station B on 13-16 March 1995. One 3-D acoustic current meter, one pressure type wave sensor, and four optical backscattering turbidity meters were deployed in the surf zone at a distance of about 120 m away from the north groin of Taichung harbor on the west coast of Taiwan (Fig. 1), in the middle of Taiwan Strait. The highest tide measured is about 5.2 m and the beach slope along the coast there is very mild, about 1/150. It is a nice place for the studying of the wave transformation in the surf zone and its interaction with suspended sediment concentration. In Fig. 2, There are three observation piles, that made of steel, 1 meter in diameter, were deployed in depths of 2, 4 and 8 meters separately along the line perpendicular to the coast. Some instruments were installed on the piles to record the temperature, barometric pressure, wind

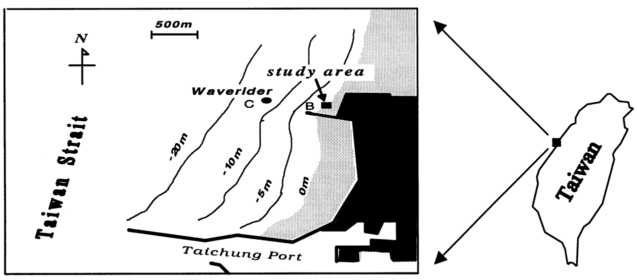


Fig. 1. Location of the field study area.

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speed, and waves out of the surf zone area. In the surf zone, the instruments were deployed in line with the wave front to make sure that the information observed by different instruments were recorded simultaneously under the very same wave conditions.

Instruments in the surf zone were deployed on the beach near the shoreline when tide was at its lowest point. Every sensor was fixed firmly in position as shown in Fig. 2. All sensors, including the topmost turbidity sensor, which was 76 cm above the sea bottom, would be submerged in water when tide varied from low water level to high water level. The pressure type wave gauge DNW-5M was installed upward at distance 20 cm above the bed and set to sample data for 2 Hz. A 3-D acoustic current meter UCM-40 was also installed at distance 27 cm above the bed, where the instantaneous current velocity induced by waves in the surf zone was recorded at rate of 2 Hz. Meantime, four optical back-scattering turbidity meters MTB-16K were deployed at distances 6.5 cm, 22 cm, 35 cm and 76 cm above the bed respectively. The observation frequency of the four turbidity meters was 1 Hz due to the limitation of the memory content available in the instruments. The processes to calibrate the turbidity meters on field sand particles ($D_{50}$ = 0.20 mm) had been done before the field experiments. Fig. 3 is the regression lines of MTB-16K for different particle diameters. Those instruments deployed were spaced about one meter in order to avoid the effects of mutual interferences. The water level, wave, current and suspended sediment concentrations were all measured simultaneously in continuous mode at station B as shown in Fig. 1. During the experiment, the significant wave heights, observed by waverider at station C as shown in Fig. 1 at depth 15 meters, were between 1.2 m and 1.5 m. The weather remained steady, and the tide difference during the experiment was about 2.6 meters.

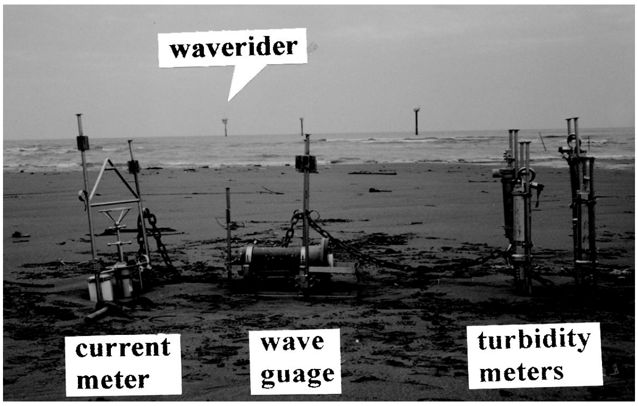


Fig. 2. Deployed instruments at Site B in the surf zone.

## THEORETICAL CONSIDERATIONS

### 1. The Empirical Mode Decomposition method

Waves in the surf zone are recognized nonlinear and non-stationary [8] due to wave breaking and shoaling effects. Historically, Fourier spectral analysis has provided a general method to analyze the wave data in frequency domain for examining its global energy-frequency distributions. Unfortunately, the requirement of system linearity, periodicity and stationarity is necessary for Fourier spectral analysis; otherwise, some spurious harmonic components will be induced to simulate the deformed wave profiles that cause energy spreading and mislead the energy-frequency distribution for nonlinear and non-stationary data.

For analyzing nonlinear and non-stationary data an Empirical Mode Decomposition (EMD) method, which is based on the local characteristic time scale of the data, was proposed by Huang *et al*. [8]. With which a data set $X(t)$ can be decomposed into a finite number of Intrinsic Mode Functions (IMF) $C_1 \sim C_n$, and a residue r, which can be left out due to the uncertainty of the trend and the interest of information contained in other components. as shown in Figs. 4 and 5.

$$X(t) = \sum_{j=1}^{n} C_j + r \tag{1}$$

Thus a sharp identification of embedded structures was given, that admit well-behaved Hilbert transforms. An energy-frequency-time distribution, designated as the Hilbert Spectrum, can then be yielded. Here, the energy is expressed by amplitude.

$$H(\omega, t) = \sum_{j=1}^{n} a_j(t) \cdot e^{i\int \omega_j(t)\,dt} \tag{2}$$

Where $H(\omega, t)$ describes the energy distribution in time domain for different frequency components; n is

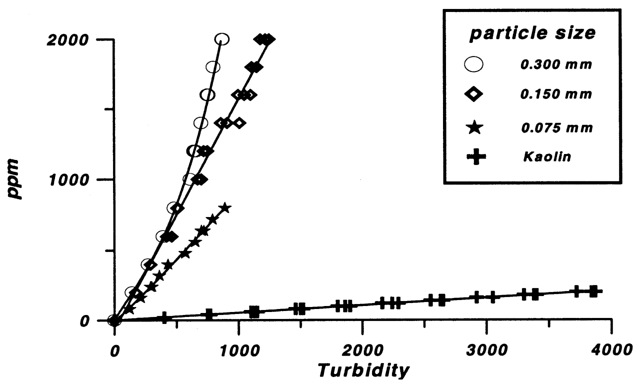


Fig. 3. Regression lines of turbidity meters for different particle sizes.

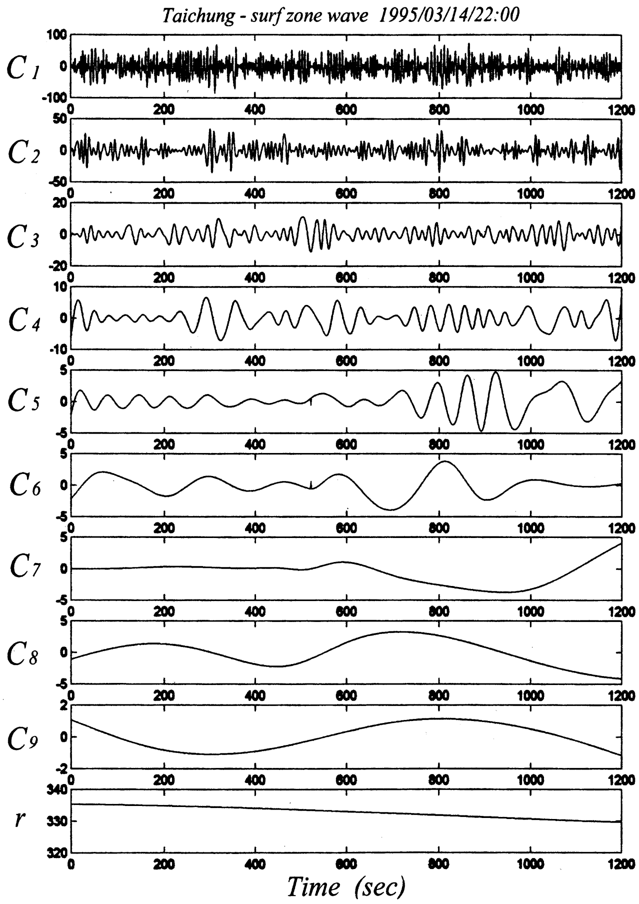


Fig. 4. IMF analysis of surface waves in the outer surf zone.

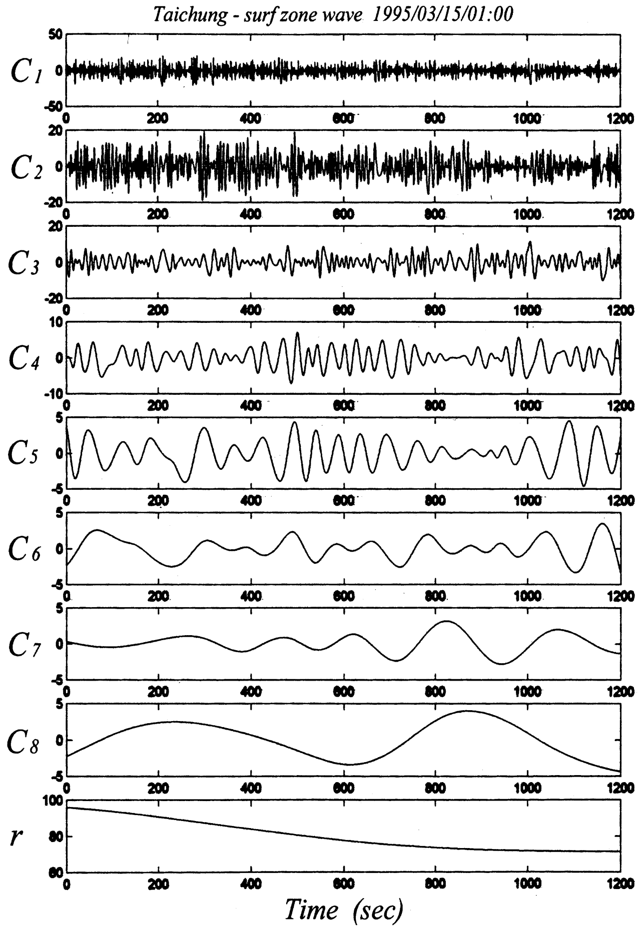


Fig. 5. IMF analysis of surface waves in the inner surf zone.

the number of IMF components decomposed; $n$ is the amplitude of each component; and $a_j$ is the instantaneous frequency changes from time to time within a wave component. The original data $X(t)$ is then represented by the real part of the Hilbert Spectrum and the residue component $r$ is left out, for it is either a monotonic function or a constant. It, however, can be included, if physical considerations justify its importance. Eq. (2) gives both frequency and amplitude of each component as function of time. To expand the same data in Fourier transform, we have

$$F(\omega) = \int_{-\infty}^{\infty} f(t) \cdot e^{-i\omega t} dt \tag{3}$$

The Fourier expansion is based on the properties of the function over the whole time span through integration. After comparing Eqs. (2) and (3), we find that the Intrinsic Mode Function represent a more generalized Fourier expansion. It improves the efficiency of the expansion, and enables us to solve the problem of non-stationary effect in the field data. Then we integrate the Hilbert energy spectrum along the time axis, a marginal Hilbert spectrum can be obtained as

$$h(\omega) = \int_0^T H(\omega, t) \tag{4}$$

where $T$ is the total data length, showing a succinct distribution of energy spectrum with wave frequency.

**2. Smoothed instantaneous wave energy history**

The smoothed instantaneous wave energy history (abbreviation as SIWEH) method for describing the phenomenon of the grouped waves was proposed by Funke and Mansard [4]. They suggested that the instantaneous wave energy of the group wave $E(t)$ can be obtained by using the moving average of the square value of $\eta(t)$ in a window time period $T_w$. The variation of the water level $\eta$ is a function of time. The definition of $E(t)$ can be shown as

$$E(t) = \frac{1}{T_P} \int_{-T_P}^{T_P} \eta^2(t + \tau) \cdot Q(\tau)\, d\tau$$

$$T_P \le t \le T_n - T_P \tag{5}$$

where $Q(\tau)$ is the Bartlett window function adopted in this paper; $T_P$ is the peak period in spectrum (let $T_w = T_P$); and $T_n$ is the total length of data.

$$Q(\tau) = 1 - \frac{|\tau|}{T_P} \ : \ -T_P \le t \le T_P \tag{6}$$

$$Q(\tau) = 0 : \ \tau < -T_P \ \text{ or } \ r > T_P \tag{7}$$

In the beginning and in the end, the data was processed as

$$E(t) = \frac{2}{T_P + t} \int_{\tau=-t}^{T_P} \eta^2(t+\tau)\, Q(\tau)\, d\tau$$

$$0 \le t \le T_P \tag{8}$$

$$E(t) = \frac{2}{T_P + (T_n - t)} \int_{\tau=-T_P}^{T_n - t} \eta^2(t+\tau)\, Q(\tau)\, d\tau$$

$$T_n - T_P \le t \le T_n \tag{9}$$

To integrate through the window function, we have the smoothed instantaneous wave energy history $E(t)$. The shape of the energy spectrum will be more peaky if the characteristics of the group wave becomes more evident.

If we use $\overline{E}(t)$ to stand for the averaged value of $E(t)$, that means the area of the wave energy spectrum, then

$$\overline{E}(t) = \frac{1}{T_n} \int_0^{T_n} E(t)\, dt = \int_0^{\infty} s(f)\, df = m_0 \tag{10}$$

where $m_0$ is the zero-th moment of the spectrum $s(f)$. Funke and Mansard [4] also proposed a groupiness factor, $GF$ to describe the intensity of group activity.

$$GF = \frac{1}{E} \cdot \sqrt{\frac{1}{T_n} \int_0^{T_n} [E(t) - \overline{E}\,]^2\, dt} \tag{11}$$

The above equation can also be expressed as

$$GF = \sqrt{m_{eo} / m_o} \tag{12}$$

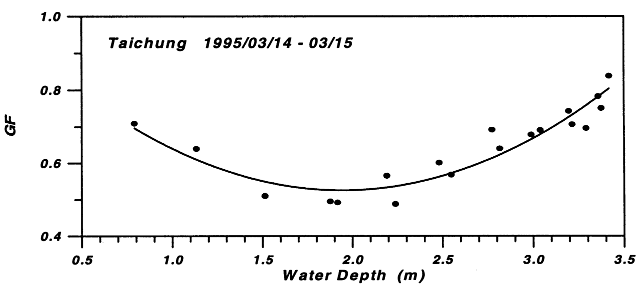


Fig. 6. Relationship between GF and the water depth in the surf zone.

where $m_{eo}$ is the total energy spectrum which obtained by the SIWEH method and $m_o$ the total energy of the incident wave spectrum. In general, the grouping effect is more evident when the ratio of the big wave amplitude to the small wave amplitude is larger.

## DATA ANALYSIS AND DISCUSSION

### 1. Wave data analysis

In order to investigate the variation of wave grouping effect for waves traveling from outer surf zone to inner surf zone. The wave gauge was set to record the water surface movement at 2 Hz in continuous mode. The data was separated and processed every 30 minutes. The group factors were computed by using Eq. (11). The result is shown in Fig. 6. It is found that water depth has great influence on the behavior of $GF$. It becomes weaker through the process of wave breaking as the wave propagates from outer surf zone to inner surf zone. The structure of grouped wave generated in the open sea is damaged and changed due to wave shoaling in the surf zone. But it becomes strengthened after passing some points in the inner surf zone.

Two data sets recorded at time 22:00 on March 14th and at time 01:00 on March 15th were selected for special attention in this paper. They represent the time of high water level while the instruments were in the place right out of the surf zone and the time of low water level while the instruments were in the inner surf zone near the shoreline respectively. The power spectra of the surface wave were computed by the fast Fourier transform (FFT) and shown as Figs. 7 and 8. The Fourier spectrum defines uniform harmonic components globally; therefore, it needs many additional harmonic components to simulate non-stationary data that are non-uniform globally. As a result, it spreads the energy over a wide frequency range. Using the Empirical Mode Decomposition method, suggested by Huang

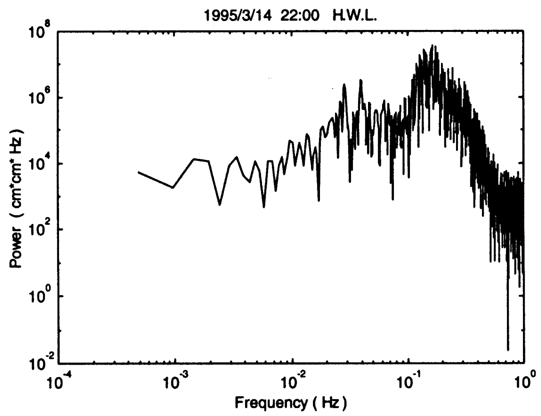


Fig. 7. Wave spectrum in the outer surf zone.

*et al.* [7], to generate a collection of Intrinsic Mode Functions $C_1 \sim C_n$ as shown in Figs. 4 and 5, representing the wave components in different frequency ranges. Where $C_1$ and $C_2$ stand for wave components of shorter period that mainly produced by the effect of wind blowing on the sea surface. The other wave components of longer period $C_3 \sim C_n$ could possibly be created by surf beat effects or edge waves that is usually prevailing in the beach area [9,10]. The shoaling effect of wave energy dissipation in the surf zone due to wave breaking and sediment entraining into water column can be clarified by the decreasing of wave height in components $C_1$ and $C_2$ as shown in Figs. 4 and 5, while the waves of longer period suffering less energy variations after progressed from outer surf zone to inner surf zone. The last component $r$ in each collection of the decomposed wave components shows the decline of water depth during the ebb tide. The grouping effects are prevalent in all frequency ranges, but not synchronized due to complicate inter-wave interactions.

Fig. 9 and Fig. 10 give the corresponding marginal Hilbert spectrums of the two data sets respectively. Without energy spreading that may happen in the Fourier spectral analysis, the marginal spectrum offers a measure of total energy contribution, expressed as sum of the amplitude h in the ordinate, from each frequency value. It represents the cumulated energy in amplitude over the entire data span in a probabilistic sense. The wave in the area right out of the surf zone is dominated by group wave [16], while the wave in the inner surf zone is dominated by long-period waves due to the surf beat phenomenon. The total wave energy in the inner surf zone has been reduced greatly through the shoaling process.

## 2. Longshore current and the induced sediment transport

A water particle trajectory plotted by connecting the current vectors in time series is shown in Fig. 11. It shows the average current speed and direction alongshore in time between 20:00 and 20:30 on March 14th. The current fluctuation due to wave motion and the long-period motions are also recorded. The average current speed alongshore was 8.8cm/s in direction WSW and the period of the long-period motions was about 7.5 minutes, a type of surf beat frequently observed in beach area [9] with moderate slopes.

The concentration profile $c(y)$ of suspended sediment in the surf zone [13] can be acquired through observations at four different positions above the bed. It can't be substituted by depth-averaged concentration due to the predominant sediment sheet-flow phenomenon in the surf zone [2,6,11] and the non-stationary

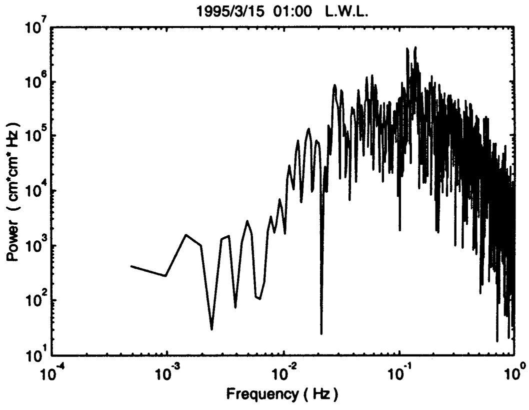


Fig. 8. Wave spectrum in the inner surf zone.

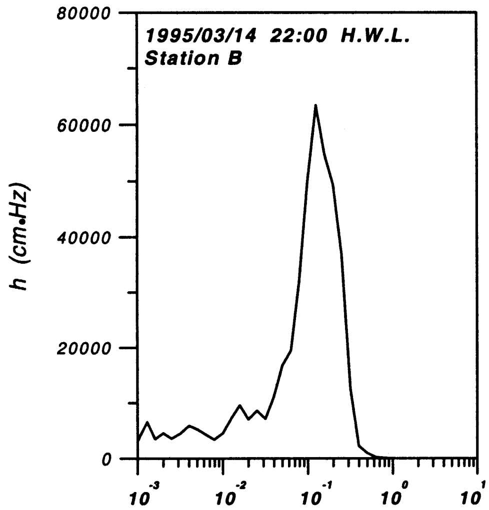


Fig. 9. The marginal Hilbert spectrum at high water level.

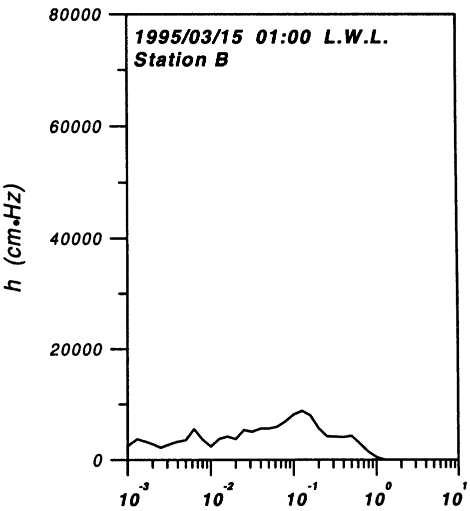


Fig. 10. The marginal Hilbert spectrum at low water level.

bursting effect of sediment concentration near the bed [5,12]. To calculate the suspended sediment transport rate qs in time series, it needs both sediment concentration profile and flow velocity profile at the same measuring point. The velocity profile can thus be substituted by $U$, which is the average value in depth, while measuring in very shallow water.

$$q_s = \int_0^D c(y)\, U dy \tag{13}$$

Where $D$ is the water depth, and $y$ is the vertical coordinate, measured upward from the bottom.

Fig. 12 shows the longshore current observed at station B (see Fig. 1). The ordinate denotes the water depth of station B at the time of observation, while the direction of coastal line is given as abscissa. During the flood tide the longshore current at station $B$ flowing in southwest direction which is in accordance with the tidal current at the open sea in this area. Interestingly, during the ebb tide the direction of the tidal current at station $C$, where the water depth is 15 m, is northeastward; while the longshore current at station $B$ is still flowing in southwest direction due to the jetty structure located to the south of station $B$ that stretches from shore to the depth of 4 m. A flow vortex is formed at the north side of the jetty during the ebb tide that makes the longshore current at station $B$ keep going southwestwards. The maximum current velocity occurred at the position of depth 2 m, which is also the position where the maximum longshore suspended sediment transport rate occurred. In the end, most of the sediment suspended in the surf zone will be transported and trapped in the north side of the jetty.

## 3. The bursting phenomenon and suspended sediment concentration

The concentration distribution of suspended sediment above the bottom was measured by four turbidity meters arranged perpendicular to the seabed at height 6.5 cm, 22 cm, 35 cm and 76 cm respectively. As the water depth changed from low water level to high water level, the position of the instrument relative to the shore line changed from inner surf zone to the area right out of the surf zone. It is found that there is a basic concentration distribution, formed by the micro substance with a prolonged suspension in the water, persisting as the background concentration during the experiment. The background concentration decreased with depth in the surf zone as shown in Fig. 13. The sampling rate of suspended sediment concentration was set to 1Hz. The concentration of the suspended sediment near the bed (6.5 cm above bottom) increased periodically in a bursting mode as shown on the bottom of Fig. 14. The periods of bursting were found in between 50 and 100 seconds, and the bursting part of the suspended sediment concentration was about 2 to 3 times the basic background concentration. The occurrence of bursting is also in accordance with wave grouping and the smoothed instantaneous wave energy history $E(t)$ as shown on the top and middle of Fig. 14 respectively. The ratio of the averaged burst concentration to the total amount of suspended sediment reaches 27.7% in the surf zone area.

## 4. The group wave and the suspended sediment concentration

The concentration of the suspended sediment near the bed increased abruptly when the wave grouping

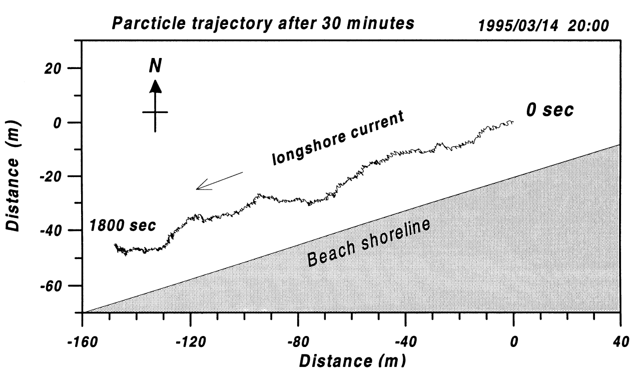


Fig. 11. The particle trajectory due to wave and long-period motions in the surf zone.

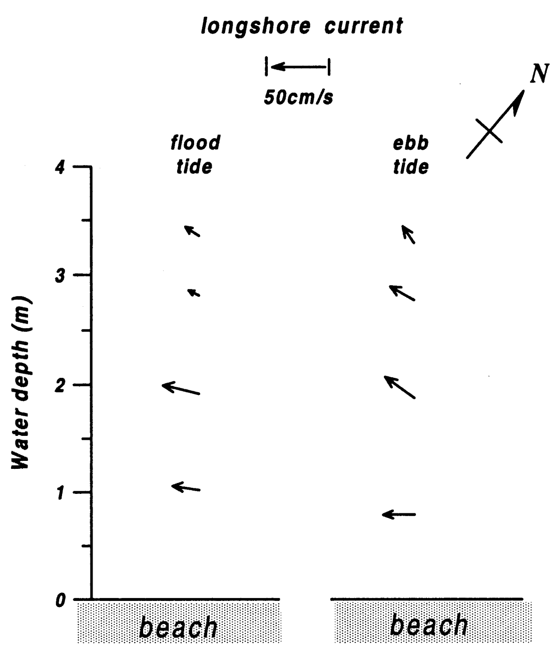


Fig. 12. The distribution of alongshore currents at station B.

occurred due to the increasing wave energy as shown by SIWEH in Fig. 14. Comparing the smoothed instantaneous wave energy and the bottom concentration of suspended sediment, the maximum cross correlation coefficient reaches 0.77 at the time lag of -0.5 sec as shown in Fig. 15, showing that the energy required to burst the bottom sediment is mainly contributed by the group waves. Examining the bursting concentration of bottom suspended sediment and the maximum amplitude occurred in the surface grouped waves, it was found that the bursting phenomenon occurred in condition that the maximum amplitude in grouped waves was greater than about 40 cm as shown in Fig. 16, and they are related as

$$\Delta C = 69.8a - 2850 \tag{14}$$

where $\Delta C$ is the excessive bursting concentration in *ppm* over the basic background concentration, and $a$ the maximum amplitude in cm occurred in each pack of grouped waves. It was also found the suspended sediment concentration near the bed was increased with the ratio of group wave height and water depth as shown in Fig. 17.

## 5. The wave energy undulating in the surf zone

Waves in the surf zone are usually non-stationary and nonlinear [8]. Historically, Fourier spectral analysis FFT has provided a general method for examining

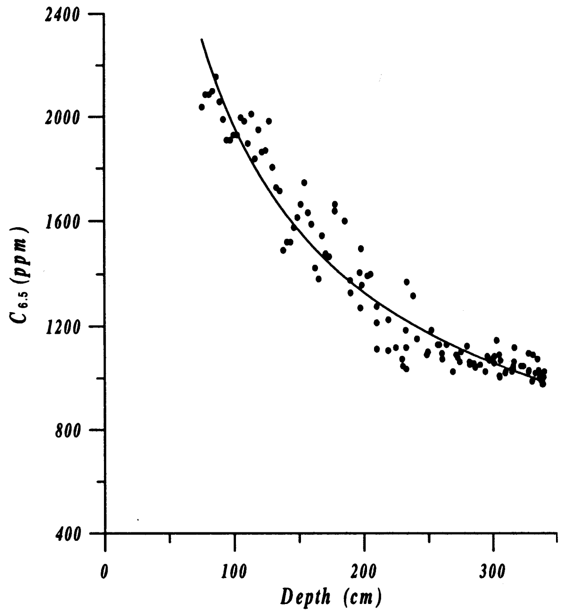


Fig. 13. The background concentrations at 6.5cm above bottom at different water depths

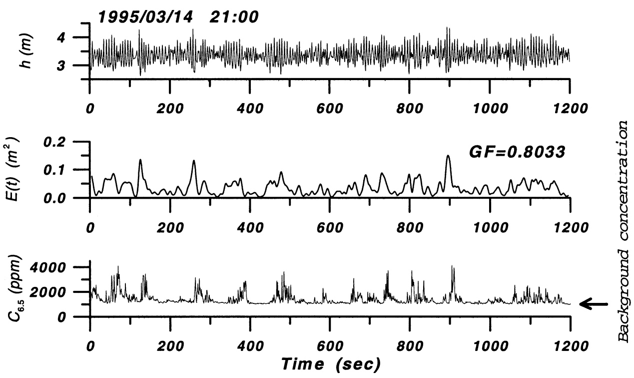


Fig. 14. The histograms of surface waves, spectrum and the corresponding near-bed sediment concentration.

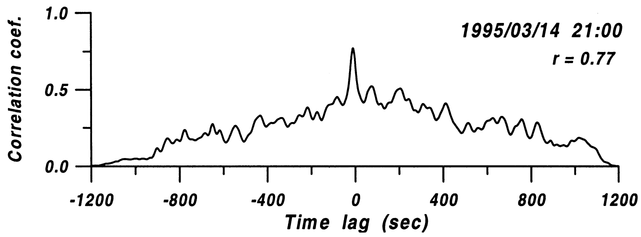


Fig. 15. Correlation between $E(t)$ and the near-bed sediment concentration C6.5.

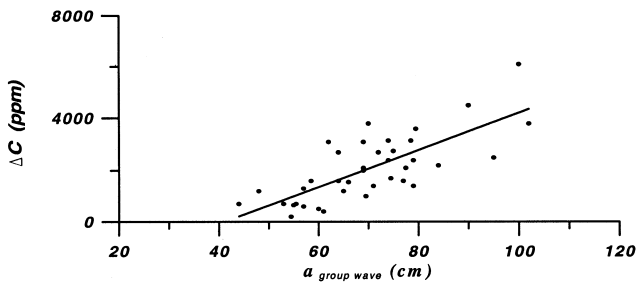


Fig. 16. The relation between bursting concentration and the amplitude of group waves.

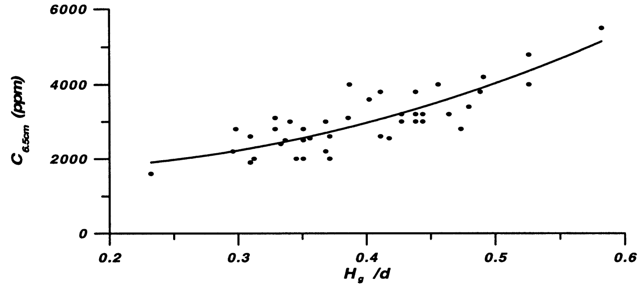


Fig. 17. The relation between near-bed concentration and the relative group wave height.

the global energy-frequency distribution, but some crucial restrictions are necessary in applying this method. It is valid under conditions of linear system and stationary data only. Recently, a new method for analyzing nonlinear and non-stationary data has been developed. Any complicated data set can be decomposed into a finite number of Intrinsic Mode Functions by the Empirical Mode Decomposition method suggested by Huang *et al*. [7]. It is based on local characteristic time scale of data, and is applicable to nonlinear and non-stationary processes. With which the Hilbert spectrum is designated to represent an energy-frequency-time distribution of data as shown in Fig. 18. In which, the ordinate is shown in logarithmic period, and the energy-period-time distribution of wave in the surf zone shows an intra-wave energy modulation in time series. The main energy is located around 10 seconds of wave period. Comparing that with the wave raw data in corresponding period of time in Fig. 19, we found that the wave energy distribution is closely related to the group wave structures. Furthermore, analyzing two different data sets, measured in the inner surf zone and the outer surf zone respectively, by the method of Hilbert spectrum gives a straightforward examination of the undulating of wave energy distribution in the surf zone as shown in Figs. 20 and 21. Waves in the inner surf zone present characteristics of lower energy and broader range of frequency distribution compares to that of higher energy and narrower range in the outer surf zone. Examining the evolution of the weakly nonlinear wave trains reveals that the process of variations are actually abrupt and local, though they have always been assumed to be globally stationary.

## CONCLUSIONS AND SUGGESTIONS

In this study, the investigation of continuous wave, current and column suspended sediment concentrations in the surf zone area at Taichung coast gives a close insight to the suspended sediment distribution and wave characteristics in the surf zone. An interesting phenomenon was found through data analysis of wave in the surf zone, a distinct harmonic frequency existed in all differential frequency components. That is the wave grouping effect spreading all over the frequency ranges in wave. Analyzing the variation of wave energy by SIWEH method, we found the value of wave grouping factor in this study area reaches up to 0.8, that implies the affection of the group wave to the suspended sediment transport was strong. By the method of EMD and Hilbert transform, the undulating of wave energy strength and shifting of peak frequency distribution in a wave train depicts the characteristics of variable inhomogeneous wave energy distribution in the surf zone.

As to the analysis of suspended sediment distribution, a periodically bursting phenomenon of the suspended sediment concentration near the seabed was found. The periods of burst were found in between 50 and 100 seconds. Also the excessive burst concentration of suspended sediment was about 2 to 3 times the basic background normal values, and the basic back-

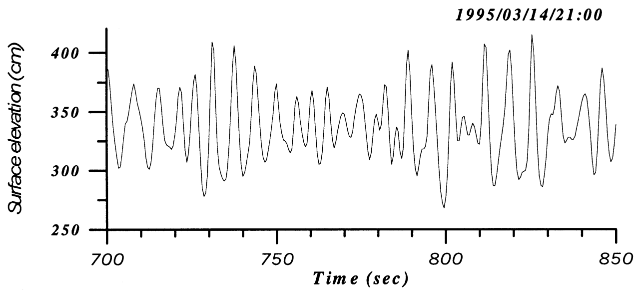


Fig. 19. The wave raw data in the outer surf zone during the corresponding period of time.

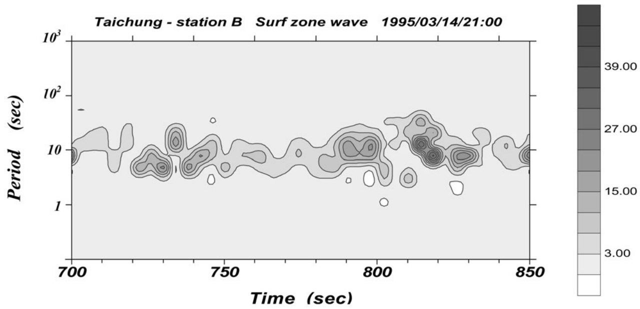


Fig. 18. The Hilbert spectrum of surface waves in the outer surf zone.

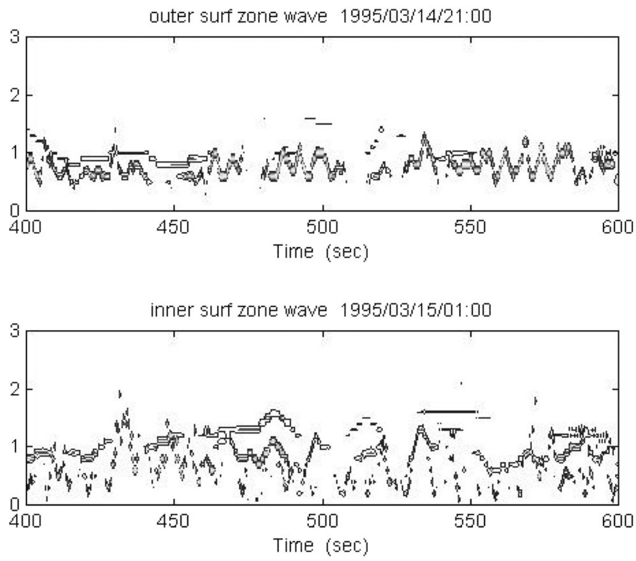


Fig. 20. The Hilbert spectrum of surface waves in the outer surf zone.

ground concentration was found decreased with water depth in the surf zone. It is because a shoaling wave in the surf zone gives stronger mixing power to the bed sediment suspension and creates higher basic background concentration. The ratio of the averaged burst concentration to the total amount of suspended sediment reaches 27.7%. It greatly affects the estimation of the near shore sediment transport rate. The empirical relationship Eq. (14), between excessive burst concentration and the maximum amplitude in each group wave, is also presented in this paper, which is useful for analyzing the near-shore sediment transport.


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