ADCP Observation of Nearshore Current Structure in the Surf Zone

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Abstract

Coastal current in the nearshore zone is generated by both breaking waves inside the surf zone and by the wind over the extended area of the coastal and offshore zones. Wind-induced currents as well as wave-induced currents are characterized by strong shear flows and complicated turbulence flow fields. In order to develop mathematical models for these currents, it is essential to formulate wind and wave stresses acting on the sea surface. Unfortunately, there has been no reliable observation of current profile in the surf zone under the condition of strong wind. No extensive information on wind stresses inside the nearshore zone has been made available, primarily because of the challenge of recording these data without facilities such as observation pier or towers.

In this paper we conducted a continuous recording of nearshore current profile and wind stresses in/out the surf zone by using high frequency ADCP (Acoustic Doppler Current Profiler, 1200kHz) installed on the sea bottom under the observation pier of Ogata Wave Observatory, together with 3-component ultrasonic anemometer. This two and half months observation revealed part of the structure of nearshore currents and some characteristics of the wind drag coefficient in the nearshore zone.

1. Introduction

Causes of beach erosion may be natural, as for example entrainment by storm waves or nearshore currents, or they may result from human activity, as for example from coastal structures, which affect waves and currents patterns, from hinterland development which reduced sediment yield, or from the global warming of the atmosphere which produces a rise of sea level. As a consequence, beaches become smaller and smaller. Management and use of the seashore may also affect water quality and the entire ecological system with its natural resources. Beaches play an important role in the global environment, yet beaches are so fragile.

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Maybe, all over the world, intensively both in the United States and in European countries, the role of beaches as a regulator of the coastal environment, as well as their function as wave absorbers (disaster prevention function) have been recognized for several decades. Soft beach construction by sand nourishment and simple structures seems to be the best choice of beach preservation. A new field, so called "Beach Engineering", emerged, in which beach protection, maintenance, and environmental and economic evaluation have been extensively examined. An interdisciplinary research on coastal environment keeps developing.

Part of this research consists of predicting the evolution of both natural and artificial beaches, and numerical simulations can be used for this purpose. Beach changes result from sediment transport which is controlled by several factors; sediments are moved away by ocean currents and nearshore currents, originated by external forces such as waves and winds. Therefore, numerical models need to combine a model for wind, a model for wave propagation and a model for sediment entrainment. Most nearshore current models have been written as horizontally two dimensional models, assuming the driving shear forces to be originated by the gradient of radiation stresses. However, these models are incomplete because it is assumed that the current profile is uniform in the vertical direction. Although the three-dimensional nature of nearshore currents has been recently studied by numerical simulations, their dynamics is not yet fully understood and their modeling remains a difficult task; to avoid the complexity of three-dimensional models which require long calculations, quasi three-dimensional models have been proposed instead. Whereas models can be run to simulate changes of sea bottom topographies induced by natural factors as well as by nearshore constructions, because of the variety of beaches, of wave and current conditions, and because of the complexity of the processes involved, the results of these simulations lack accuracy. Field observations can then be used as a complementary source of information to understand current mechanisms, long-term beach evolution, and to calibrate the models in each particular case. This requires a substantial amount of data simultaneously for winds, waves and currents in order to calibrate each part of the code - wind module, wave module and current module - as well as the whole coherence of the model. For example, test runs can be performed and model parameters adjusted until numerical results fit field data.

Such a long term observation was carried out by Yamashita et al. (1997) to investigate the structure of nearshore currents in the surf zone along the Ogata coast facing the Japan Sea. Since most erosion occurs in presence of large waves and strong winds, data were recorded during winter time, under such conditions. After an observation of two months, the following characteristics were revealed : (1) nearshore currents have almost uniform vertical distribution in the surf zone, (2) nearshore currents are strongly influenced by the wind, and wind-induced currents are of the same order as wave-induced currents. It was also observed that features of waves, currents and turbulence differ significantly from shallow waters to deep waters. Therefore, mechanisms of momentum transfer between atmosphere and sea deserve further investigations. Effects of both waves and winds need to be taken into account in any nearshore current simulation along this coast.

It is the goal of this study to discuss some aspects of winds, waves and currents recorded in the surf zone and to get a better understanding of their mutual interaction; the observation was made possible by the presence of the T-shaped observation pier (TOP) of Ogata Wave Observatory, a research facility of the Disaster Prevention Institute (DPRI), Kyoto University. This pier extends from the shoreline into the surf zone and permits continuous and methodic recordings of nearshore data in an area inaccessible by boat under severe winter conditions. The pier also enables constant check out and maintenance of all instruments. Nearshore currents were recorded by two ADCPs. Winds were recorded by a three-components anemometer at a 10m elevation above mean sea level. The influence of wind and waves on current intensity and direction were investigated. A drag coefficient was derived to characterize wind stresses over the surf zone. The drag coefficient was deduced from wind data using the Turbulence Dissipation Method (TDM).

2. Observation of Currents, Waves and Winds in the Nearshore Zone

During winter time, severe erosion is caused by offshore sediment transport along the Japan's coast facing the Japan Sea. It is believed that the strong winds and waves take a significant role in this process, but the mechanisms involved are not yet understood. In this study, the interdependence between winds, waves and currents is examined, based on a set of data recorded in/out the surf zone in order to get a preliminary idea on nearshore-currents structure and dynamics. The observation was carried out using the pier (TOP) with the following instruments: 3-component ultrasonic anemometer for wind shear stresses, seven ultrasonic wave gauges for water surface elevation and wave characteristics and two 1200KHz ADCP set on 1.3m above the sea bottom underneath the pier for current profiles. Dimension and location of instruments are shown in Fig.1.

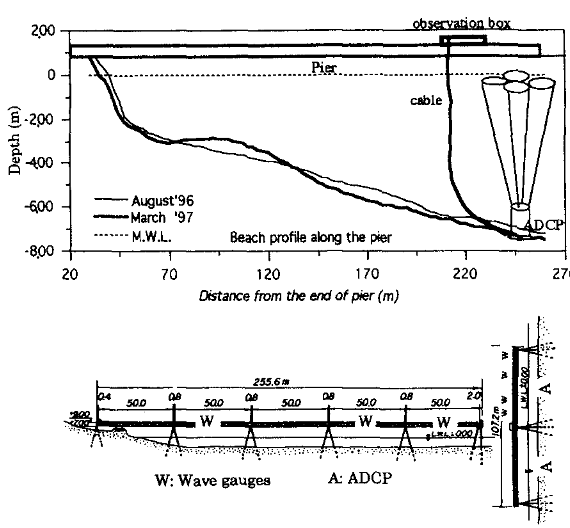

Figure 1 T-shaped observation pier, beach profile and location of instruments

Figure 2 shows (a) the significant wave height of the wave gauge ch.4 and 5, (b) offshore and (c) longshore velocities (4-6m depth average of west ADCP) during the entire observation period. As been shown in Fig.2(b), seven winter storms which generated strong offshore-going currents were recorded. Five cases of them, Case A (Jan. 4-5), Case B (Jan. 6-7), Case C (Jan.18-20), Case D (Jan.31-Feb.1) and Case E (Feb.9-10), are selected to investigate the interdependence between nearshore currents and wind-wave climate. It is observed that strong offshore currents arise only during short periods of less than 24hrs and longshore currents going eastwards are dominant.

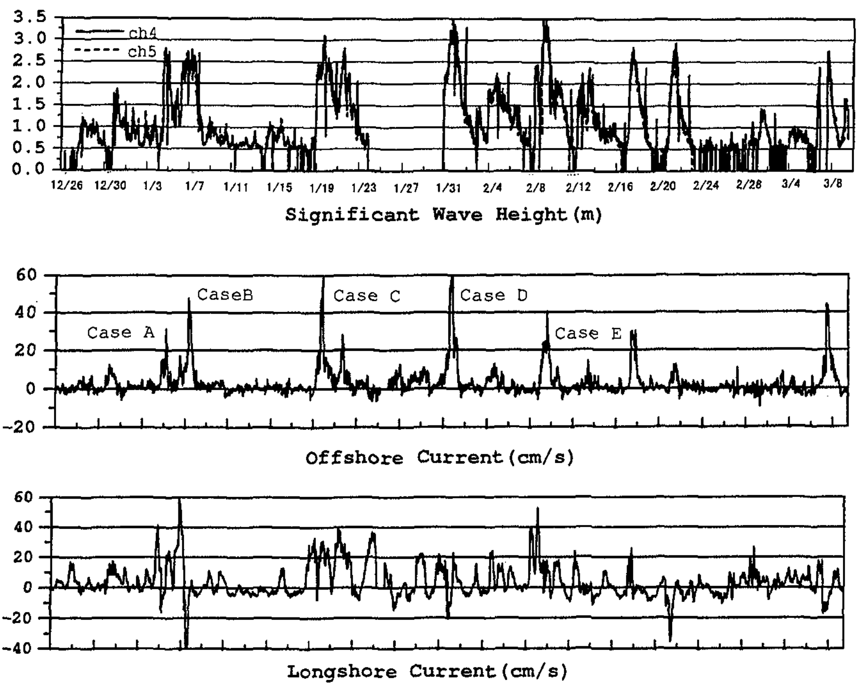

Figure 2 Significant wave height (ch.4 and 5), and 4-6m depth averaged currents of the west ADCP recorded during the entire observation period. Cases A-E indicate the selected ivents in which strong offshore going currents observed.

Top: significant wave height of the wave gauge ch.4 and 5, Middle: offshore velocity (going offshore is positive), Bottom: longshore velocity (going eastwards is positive)

3. Interdependence between Nearshore Currents and Wind-Wave Climate

Figures 3 - 7 show interdependence between nearshore currents and wind/wave climate of five selected winter storms (Case A-E in Fig.2(b)). Sub figures refer respectively to time (a) wave climate, (b) wind climate, (c) longshore current profiles, (d) offshore current profiles and (e) nearshore current profiles by vector. As TOP is oriented north-west (48deg from the north, shore-normal), winds blowing from a direction westwards relative to TOP will be referred to as westerly winds. During winter storm winds typically blow from the west, i.e. they are westerly relative to the pier. From these figures, it can be recognized that there are two types of wind/wave climates which cause strong offshore-going currents. One is the type called "end-storm undertow" which is defined that sudden bursts of current occur with changes in wind directions from westerly to easterly with reduction of wind velocity at the end of the winter storms (Cases A, B, E). The other is the type called "mid-storm undertow" which is defined that continuous strong shore-normal(NW) winds generate strong undertow in the midst of storm (Cases C, D). It has been recognized at TOP that when the significant wave height at the gauge ch.4 exceeds 2.5m, TOP is completely inside the surf zone, and when being the range of 2.0-2.5m, breaker point exists in the area of gauge ch.4 to ch.6. If the obvious reduction in the significant wave height between ch.5 and ch.6 is observed, we judge that wave breaking occurred between ch.5 to ch.6. Following are significant nearshore-current characteristics revealed by the 1998 observation:

(a) Velocity profile : Sub figures (c) and (d) in Figs. 3-7 indicate that both longshore and offshore current profiles in the vertical direction are almost uniform in the region under the wave trough level and above the boundary layer when wave and wind climates are stable. Figure 8 shows the hourly changes in vertical profiles of on-offshore (left) and longshore (right) in Case B. Phases A, B and C in the figure are indicated in Fig.4, which are corresponding to before, middle and after the sudden bursts of offshore-going currents.

(b) Longshore currents : Direction of longshore currents is much more sensitive to the wind direction than waves. Its intensity is much stronger than that of on-offshore component except the phase of the sudden bursts of offshore-going currents. These observation facts may indicate that strong longshore current is mainly induced by winds in the wide area of nearshore zone and its direction is shore-parallel. Wave-induced longshore current is much smaller than wind-induced one. This fact suggest us that wind-induced current near the surf zone is the dominant factor of sediment transport under the storm conditions such as typhoon, hurricane and winter monsoon. This effect should be taken into consideration when beach changes and depth of closure are discussed.

(c) On-offshore currents : As mentioned before there are two types of wind climate which cause a strong offshore-going current, those are called here "end-storm undertow" and "mid-storm undertow". These cross shore currents may be generated by unbalance of mean water surface gradient and shear stresses due to both winds and

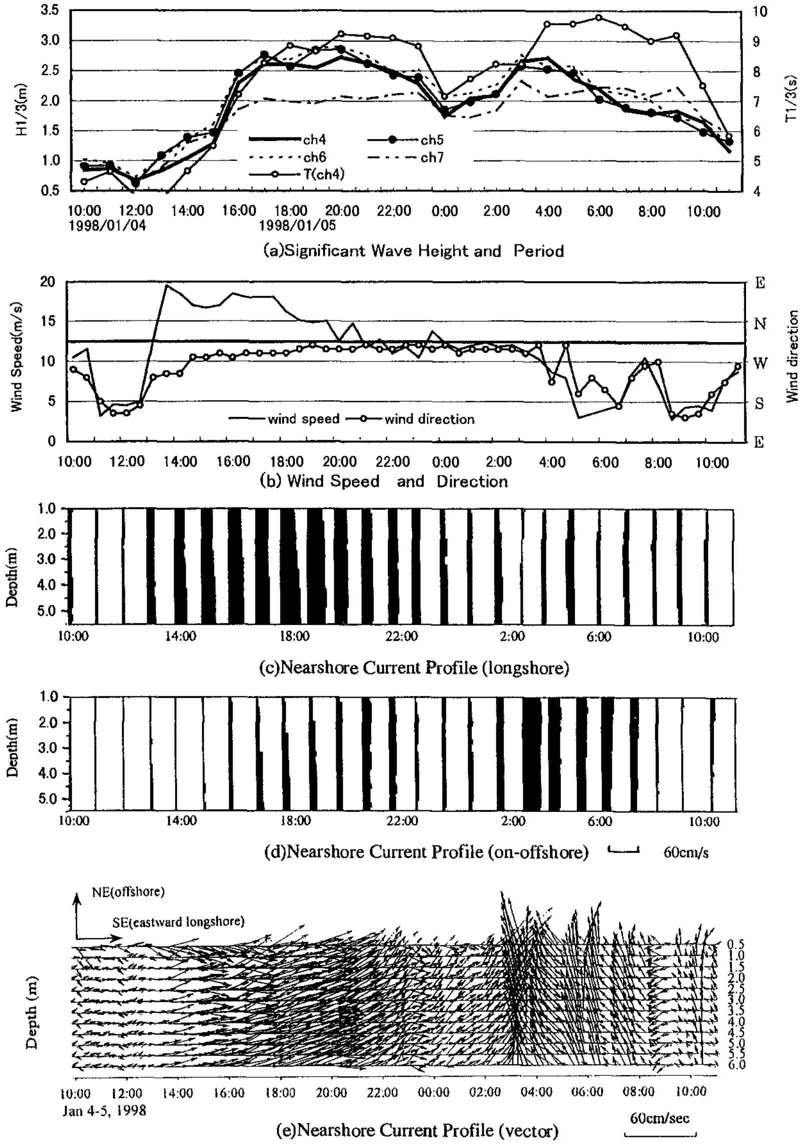

Figure 3 Interdependence between nearshore currents and wind/wave climate of winter storms (Case A).

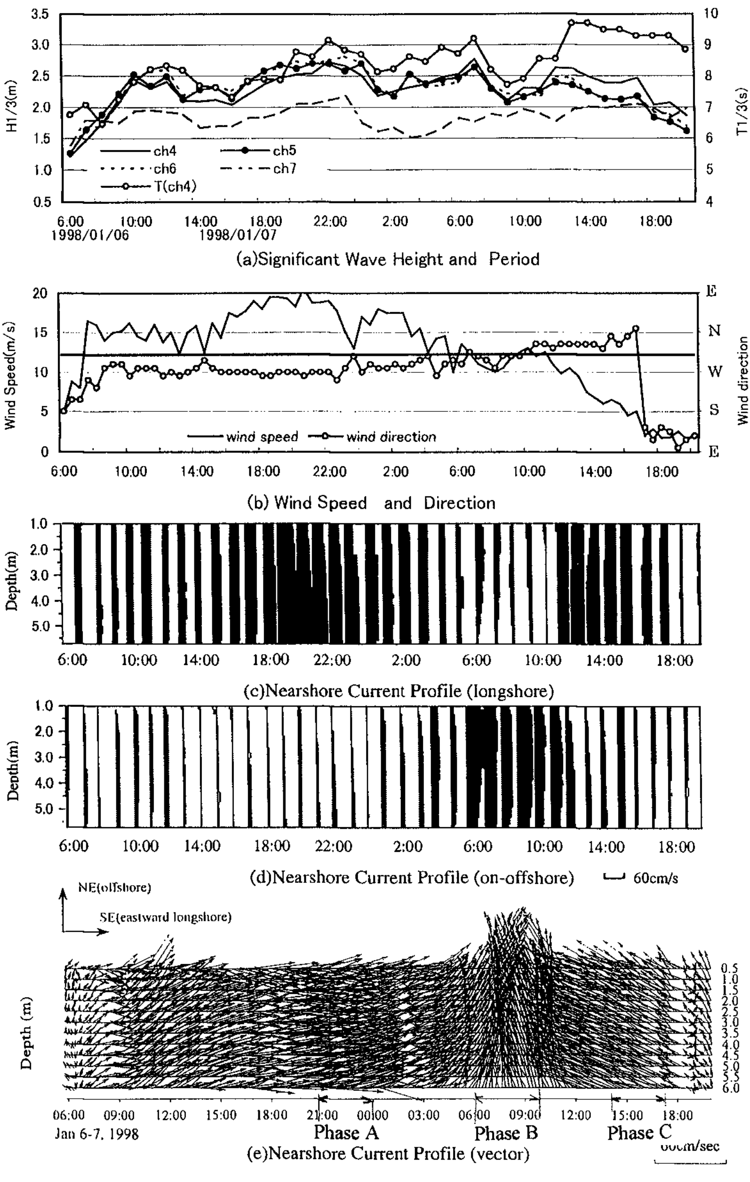

Figure 4 Interdependence between nearshore currents and wind/wave climate of winter storms (Case B).

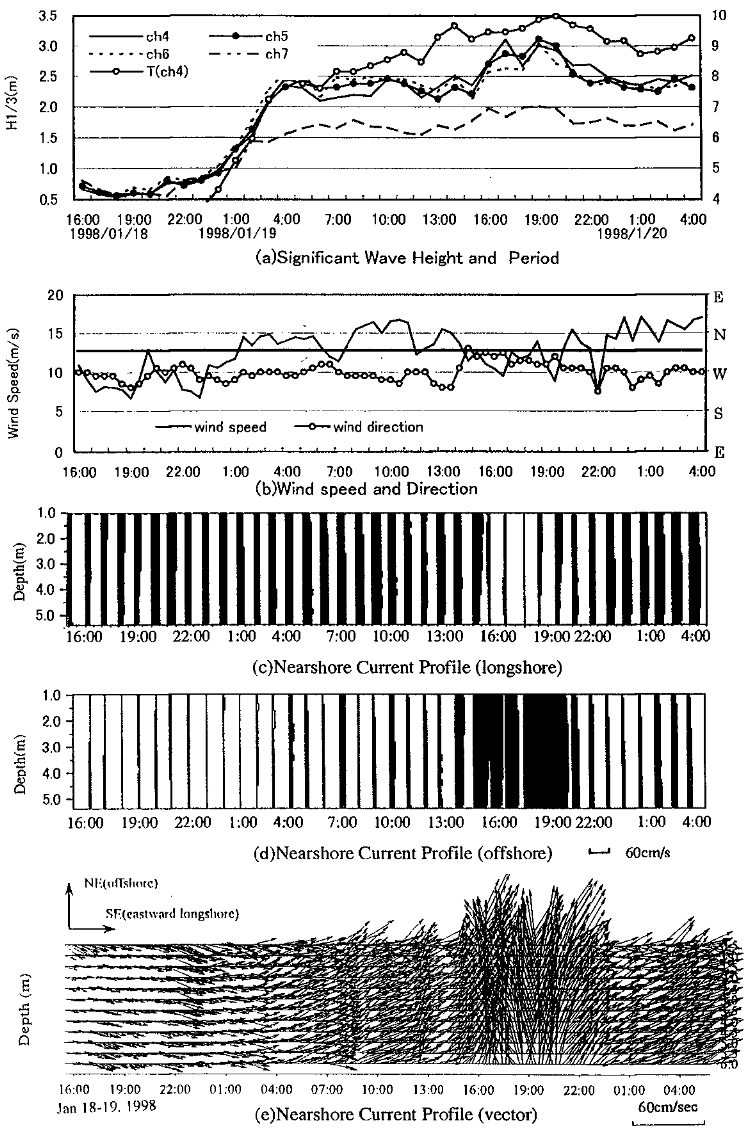

Figure 5 Interdependence between nearshore currents and wind/wave climate of winter storms (Case C) .

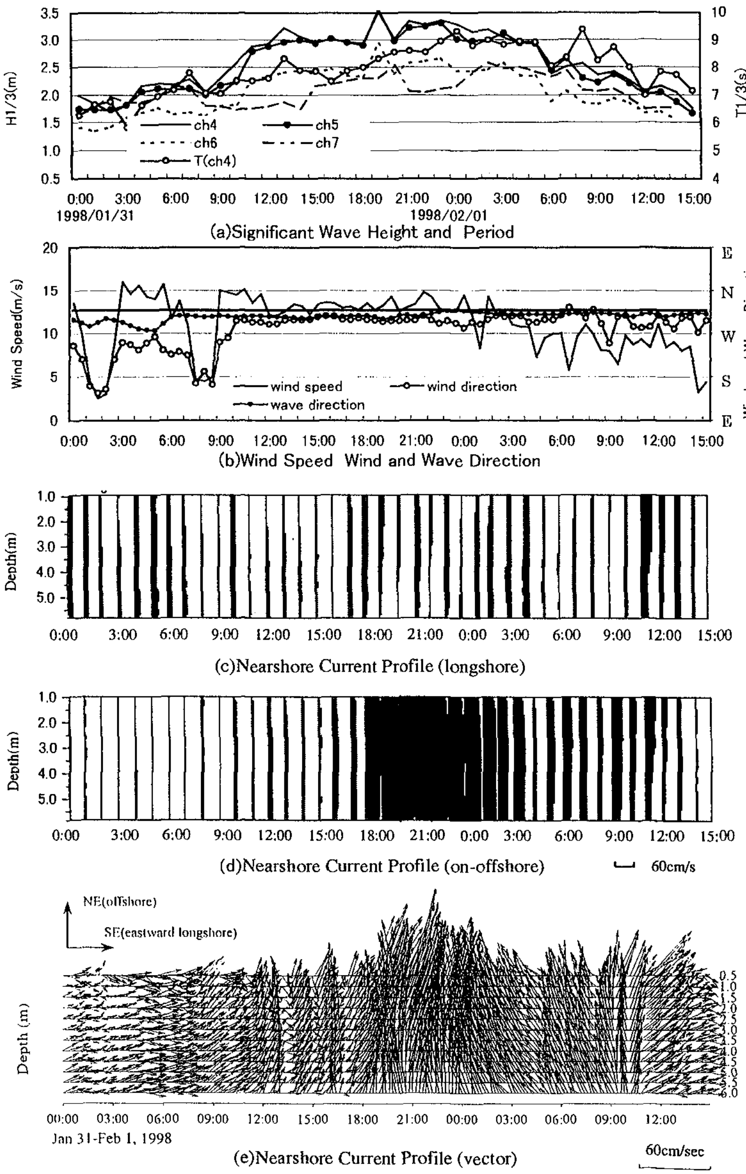

Figure 6 Interdependence between nearshore currents and wind/wave climate of winter storms (Case D).

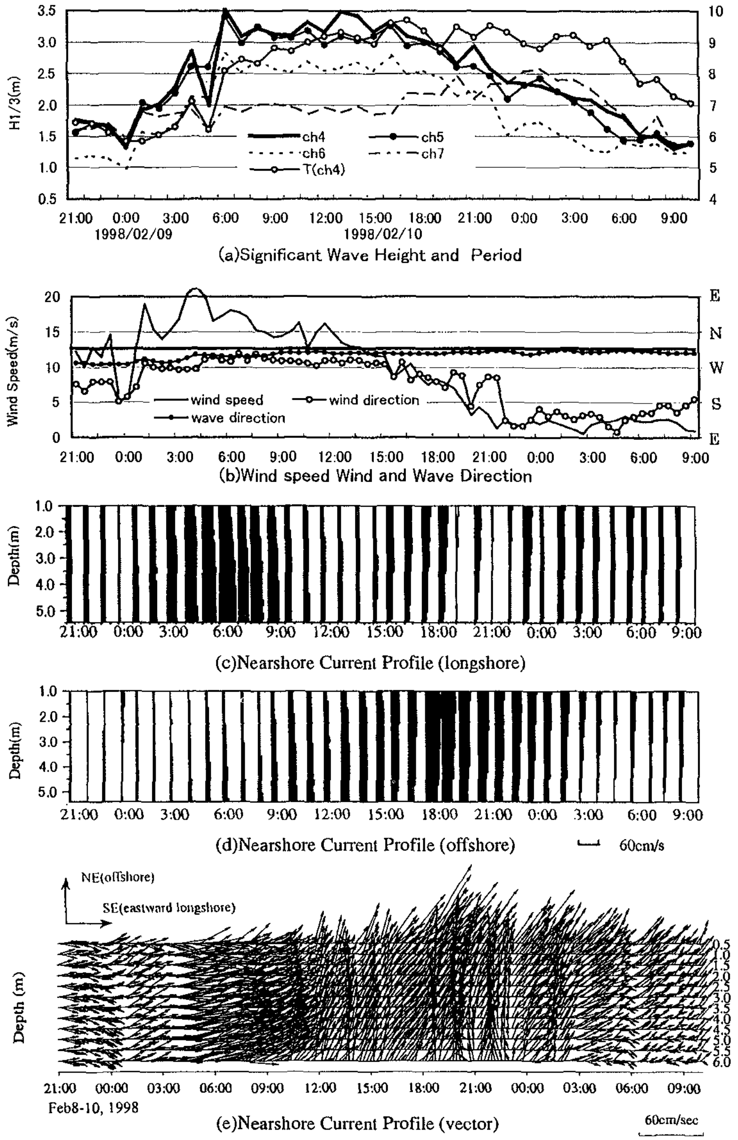

Figure 7 Interdependence between nearshore currents and wind/wave climate of winter storms (Case E).

breaking waves. When wind direction changes and/or wind velocity decreases at the end of winter storm, the type of "end-storm undertow" occurs. When the water surface gradient which is generated by wind and wave-induced cross shore currents loses its balance in the midst of the storm, the type of "mid-storm undertow" occurs. Wave-induced cross shore currents is mainly generated in the surf zone by wave breaking, which may form the velocity profile of the so-called undertow together with wind-induced cross shore currents. Note that the mechanism of this undertow is different from two types of strong offshore-going currents. The intensity of offshore-going sediment transport by "end-storm undertow" and "mid-storm undertow" may have to be made clear to evaluate the total volume of losing sand by storms.

4. Wind Stresses in the Nearshore Zone

As wind-induced current is the main factor of sediment transport, especially longshore transport, evaluation of wind stresses in the nearshore zone is one of the most important tasks of beach change prediction under the storm condition. Stress factors represent the exchange of momentum between atmosphere and ocean, and between ocean and sea bed. Air-sea momentum exchange is controlled by the waves; it is a complex process involving turbulent boundary-layer flow over a moving rough surface, wave generation, non-linear energy transfer between wave components, and wave breaking. Besides, waves also affect the bottom stress by increasing turbulence in the bottom boundary layer and eddy viscosity, hence facilitating momentum transfer. These processes are not very well understood theoretically, especially under strong winds and high waves, and therefore they are not incorporated into the models. If they could be better explained, then, in principle, the accuracy of the corresponding forcing terms in the equations of motion for nearshore currents could be improved.

Following is an analysis of wind data over the surf zone aimed to formulate wind stresses in terms of a drag coefficient. Wind turbulence was measured by a three-components ultrasonic anemometer, located on top of the observation pier, 10m above the mean sea level. Wind data were continuously recorded at a 10Hz sampling frequency, and analyzed by means of the Turbulence Dissipation Method (Yelland et al. ,1996). Wind data observed have been classified into four types according to the wind direction relative to the pier (TOP), as defined in Fig. 9. Almost all winds stronger than 10m/s are from the direction of south-west to north-west (Type I), in which the drag coefficient, C_D, estimated by TDM (10min in every hour) and the average wind speed at 10m, U, obey a linear relationship in a semi-log plot as shown in Fig. 10. The following fitting formula has been obtained:

$$C_D = 0.0223\left(\frac{10}{3}\right)^{-\frac{U}{15}} \tag{1}$$

The drag coefficient usually increases with the wind speed in the ocean, but observed drag coefficient indicates the opposite tendency in the nearshore zone. The effect of long-crestedness and steepness of waves in the shallow water may cause larger drag coefficient and wave breaking may cause such an inverse trend vs wind speeds.

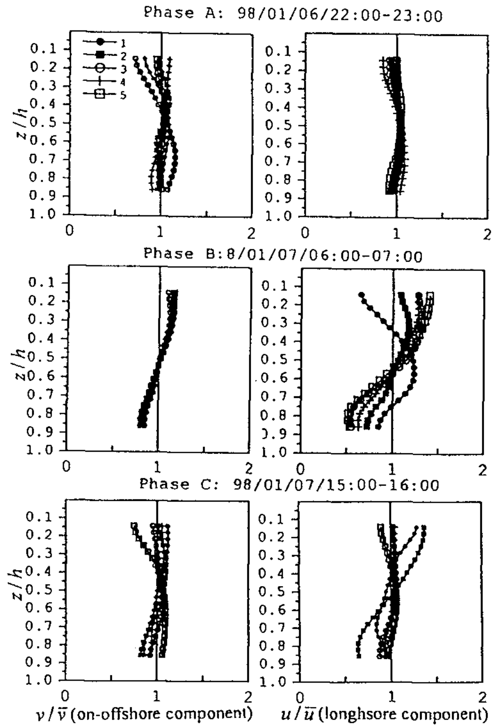

Figure 8 The hourly changes in vertical profiles of on-offshore (left) and longshore (right) in Case B.

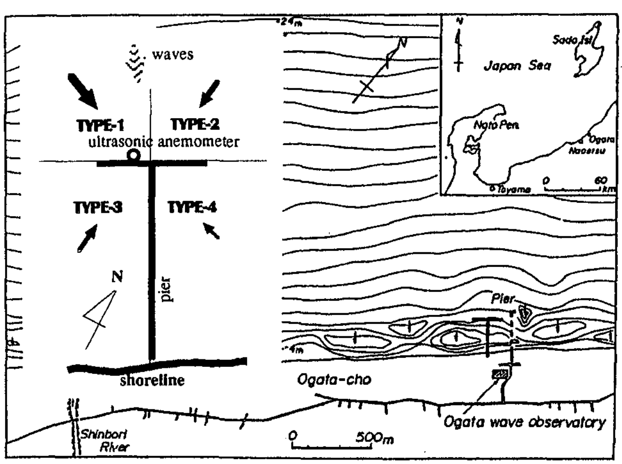

Figure 9 Wind data classification (four types) according to the wind direction relative to the pier (TOP).

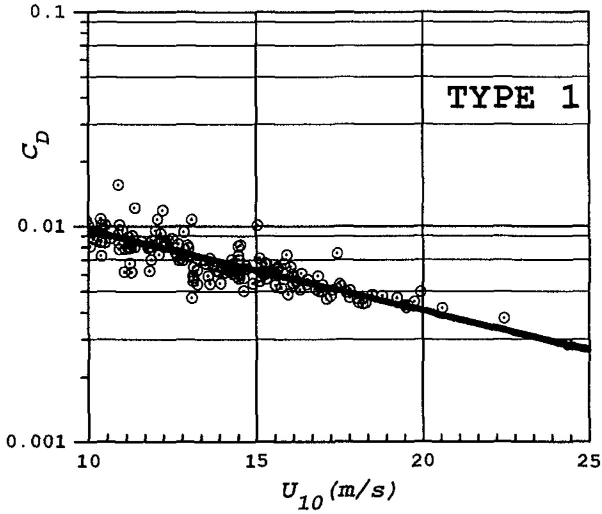

Figure 10 The drag coefficient estimated by TDM and the averaged wind speed.

5. Conclusions

This study is a screening of a set of wind and current data recorded in the surf zone during a two and half months period from an observation pier. Winds and waves were observed simultaneously and continuously in the nearshore zone, at a location alternately inside the surf zone and outside, depending on the state of the sea. This long-term observation revealed the structure of currents and the characteristics of the wind drag in the nearshore zone; main results are summarized below :

(1) There are two types of wind/wave climates which cause strong offshore-going currents. One is the type called "end-storm undertow" which is defined that sudden bursts of current occur with changes in wind directions from westerly to easterly with reduction of wind velocity at the end of the winter storms. The other is the type called "mid-storm undertow" which is defined that continuous strong shore-normal(NW) winds generate strong undertow in the midst of storm.

(2) Both offshore and longshore current profiles are vertically uniform underneath the wave trough level.

(3) Direction of longshore currents is much more sensitive to the wind direction than waves. Strong longshore current is mainly induced by winds in the wide area of nearshore zone and its direction is shore-parallel. Wave-induced longshore current is much smaller than wind-induced one.

(4) Wave-induced cross shore currents is mainly generated in the surf zone by wave breaking, which may form the velocity profile of the so-called undertow together with wind-induced cross shore currents.

(5) Drag coefficient in the near shore zone was empirically formulated with relation to the wind speed in the range of over 10m/s, which shows the opposite tendency to that in deep waters.

Acknowledgements

The authors would like to express our thanks to Mr. Kiyoshi Uchiyama, technician in Ogata Wave Observatory, for his kind help in observations. This study was funded by the Ministry of Education, Science, Sports and Culture of Japan as the Research Project, Grant-in-aid for Scientific Research (1997-1998), contract No.09555157, (the chief researcher, Takao Yamashita, Kyoto University). Support for a part of observation was also received from the NEWJEC Consultants Inc, Osaka, Japan.

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