CHAPTER 298

Sediment Movement and Stress Condition in Sea Bed

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ABSTRACT

The stress condition in the sea bed such as effective stress and hydrodynamic condition were measured in the surf zone to understand the detailed mechanism of local and temporal sediment movement. Analysis of the measured data suggests that the large effective stress drop and strong flow in the onshore direction when the wave crest passes are the possible cause for the sand movement in the surf zone. It is also found that the sea bottom elevation change can be evaluated from the effective stress in the sand by a simple equation. The effective stress sensor used in the field measurement was proved to be useful in estimating local and temporal sediment transport.

INTRODUCTION

Sediment transport is usually studied in terms of wave condition and characteristics of bed material. However, in order to understand the detailed mechanism of local and temporal sediment movement, it is important to associate the stress condition in sea bed with wave condition and then to relate the stress to sediment transport. For example, Nago(1982) pointed the relation between the pore pressure and fluidization of the bed.

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Maeno and Hasegawa(1985) examined the effects of wave-induced pore pressure in sand bed on liquefaction. Maeno and Tokutomi(1989b) indicated the strong correlation between the liquefaction of sand bed and the mechanisms of sediment transport. Maeno (1992) introduced the experimental results on wave-induced liquefaction and sediment transport, and indicated the needs of the further verification by field observation.

Maeno *et al.*(1993) measured the effective stress, pore pressure and wave conditions outside the surf zone, and concluded that liquefaction occurs by the delayed response of the pore pressure to the surface elevation change. In this research, the similar approach was taken, and the bottom elevation change was tried to relate to the effective stress, pore pressure, wave height and current velocity, which were measured in the surf zone.

This research also attempts to examine the performance of a newly developed effective stress sensor (Maeno *et al.*, 1992), which may give the local and temporal information that are hard to obtain by the conventional methods; sand trap, surveying, etc.

FIELD MEASUREMENT

Measurement Site

Measurement was made in a beach at Hazaki-cho, Ibaragi Prefecture, Japan (see Figure 1). This beach is a part of 80 km straight sandy coast facing the Pacific Ocean. There is a 427 m long observation pier on the beach owned by Port and Harbour Research Institute, Ministry of Transport, to study sediment transport. This study made use of the pier, from which various data were taken. Two measurement locations were chosen in the surf zone along thc pier: one is 230 m offshore from the shoreline and the other is 260 m offshore. Figure 2 illustrates the measurement locations and the bottom profiles under the pier during the measurement period. The water depth at those locations fluctuated in the range of 1 m, but both the locations remained on a large bar.

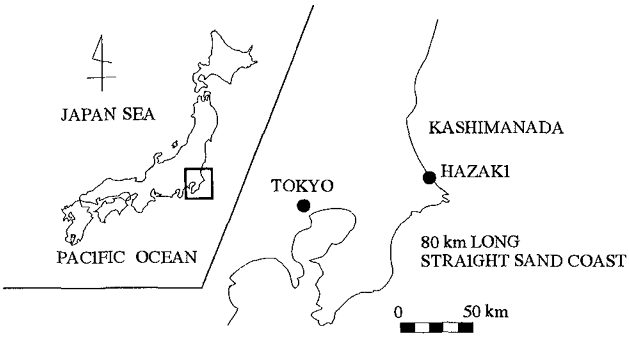

FIG. 1. MEASUREMENT SITE

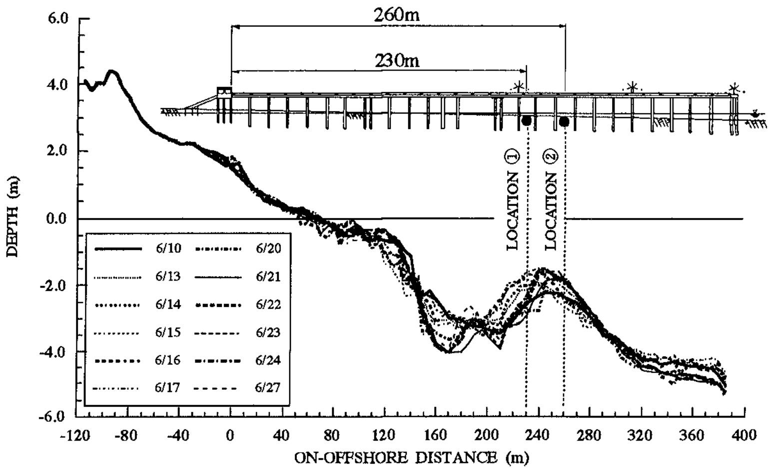

FIG. 2. MEASUREMENTS OF SEA BOTTOM PROFILE

Instruments

The instruments deployed in the measurement locations are listed in Table 1. To install these instruments, a frame structure was put in sea bed at each location as shown in Figure 3. It held an effective stress sensor and a dynamic pore pressure gauge in the sea bed, a pressure gauge on the sea bed, a current meter, and a wave gauge. The effective stress sensor and dynamic pore pressure gauge were the differential type made of the flexible filter (Maeno and Tokutomi,1989a). Additional data such as sea surface elevation by acoustic wave gauge, wind data, water depth and ground water level were supplied by Port and Harbour Research Institute, who takes these data at the pier on a regular basis. The measured data were recorded at 10 Hz from June 12th to 26th, 1994 for the location 1 and from June 12th to 15th for the location 2. Data acquisition was terminated by the damage to the measurement system due to the high seas.

MECHANISM OF LIQUEFACTION

From a soil mechanical point of view, the sand can be mobilized when the stress acting on it exceeds its capacity. The sand in the zero or negative effective stress condition, which may be called liquefaction, is certainly the case. How liquefaction takes place outside the surf zone was explained (Maeno *et al.*, 1993), and this study focuses on the condition in the surf zone. The mechanism of liquefaction outside the surf zone is reviewed first, and the mechanism in the surf zone found by analyzing the data measured in the present study is followed.

TABLE 1. SUBJECTS FOR MEASUREMENT

MEASURING SUBJECTS	MEASURING EQUIPMENTS	REMARKS
DYNAMIC PORE WATER PRESSURE	DYNAMIC PORE WATER PRESSURE TRANSDUCER	1.0m BELOW SEABED SURFACE
EFFECTIVE EARTH PRESSURE	EFFECTIVE EARTH PRESSURE TRANSDUCER	1.0m BELOW SEABED SURFACE
WATER PRESSURE	WATER PRESSURE TRANSDUCER	1.0 m ABOVE SEABED SURFACE
WAVE PROFILE	ULTRASONIC-TYPE WAVE GAUGE	AIR BEAM TYPE
	CAPACITANCE-TYPE WAVE GAUGE	
VELOCITY	ELECTROMAGNETIC VELOCIMETER	1.0 m ABOVE SEABED SURFACE
WIND DIRECTION AND WIND VELOCITY	PROPELLER-TYPE WIND VANE AND ANEMOMETER	385m OFF SHORELINE
SEA BOTTOM PROFILE	SOUNDING	DAILY MEASURING

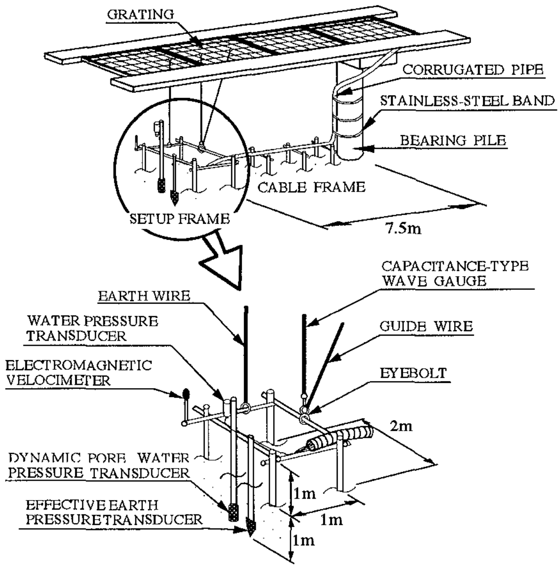

FIG. 3. INSTALLATION OF INSTRUMENTS

Outside Surf Zone

Generally, the dynamic pore pressure and effective stress in the sea bed follow the sea surface elevation change. However, it was found from close observation of these data taken outside the surf zone (Maeno *et al.*, 1993) that the dynamic pore pressure is slightly lagged behind the change of the sea surface elevation. This yields excessive positive effective stress at crest and negative value after the crest passes to compensate for the insufficient pore pressure response. The negative part of the effective stress gives rise to the liquefaction of the sand, which can be swept away by the currents near the bed. This process is illustrated in Figure 4. Figurc 5 shows the time histories of the stresses measured at a depth of 6 m (Maeno *et al.*, 1993). Sharp peaks are observed in the effective stress record due to the late response of the pore pressure to the surface elevation. The magnitude of the negative peak indicates the thickness of the sand layer that was liquidized, and the difference in the stress level before and after the wave is equal to the thickness of the sand layer that was washed away. In this example, the sand in the top 47 cm thick layer was liquidized and the sand layer in the thickness of about 17 cm was carried away.

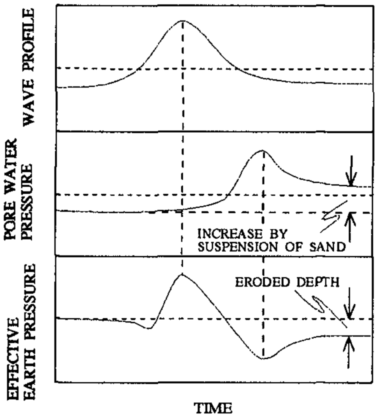

FIG. 4. MECHANISM OF LIQUEFACTION OUTSIDE SURF ZONE

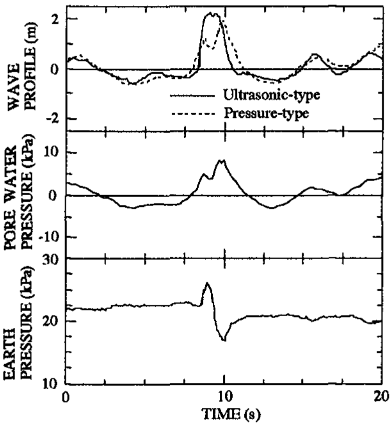

FIG. 5. TIME HISTORIES FOR STEEP AND LARGE WAVE HEIGHT

Inside Surf Zone

In this study the similar kinds of data were collected in the surf zone. Figure 6 shows the responses of those stresses collected at location 2, where waves were steep enough to break. In this case there is little time lag in the response of the pore pressure, which is different from the stress response outside the surf zone. The wave action in the surf zone is severer and the top layer of the sand is more likely to be loose so that the pressure exerted on the sea bottom is transmitted instantaneously to inside.

The response of the effective stress is characterized with the sharp and large drops when the wave crests pass. These drops become larger as the wave height increases. The magnitude of this drop is much smaller than that of the pore pressure, and the negative effective stress may be due to the overshooting response of the pore pressure.

The current data at the sea bottom in Figure 6 show the strong flow in the onshore direction when the crests pass and the effective stress is very low. It is surmised that the loose sand in the top layer where the effective stress is nearly zero may be carried

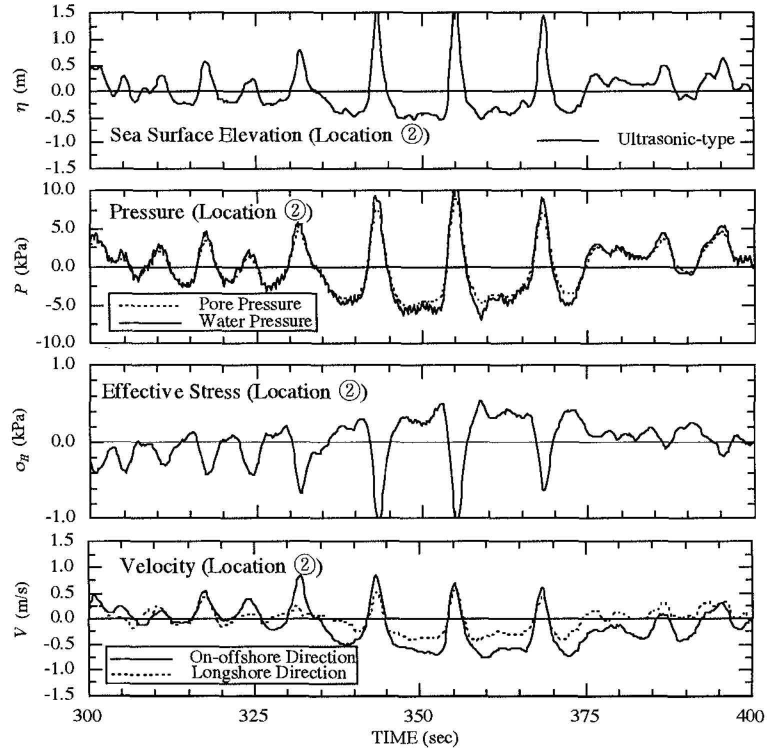

FIG. 6. TIME HISTORY DATA AT LOCATION 2 (6/15/1994 01:17:16)

away by the strong onshore flow. Compared with the condition outside the surf zone, the larger negative effective stress and stronger current due to severer wave action are expected in the surf zone. The condition in the surf zone that large negative effective stress and strong current occur at crest is one of the mechanisms for the sediment movement in the surf zone

ANALYSIS OF FIELD DATA

Wave Condition

The significant wave height and period, and wind information are computed based on 50 minutes-long data to represent the condition at that hour, and are shown in Figure 7. There were two moderate storms with approximately 2 m significant wave height coming in the measuring period: on 15th to 16th and on 19th to 20th. The swells were dominant at the first event, since wind was weak and the wave period was relatively long. On the other hand, the second event was cause by the strong easterly winds.

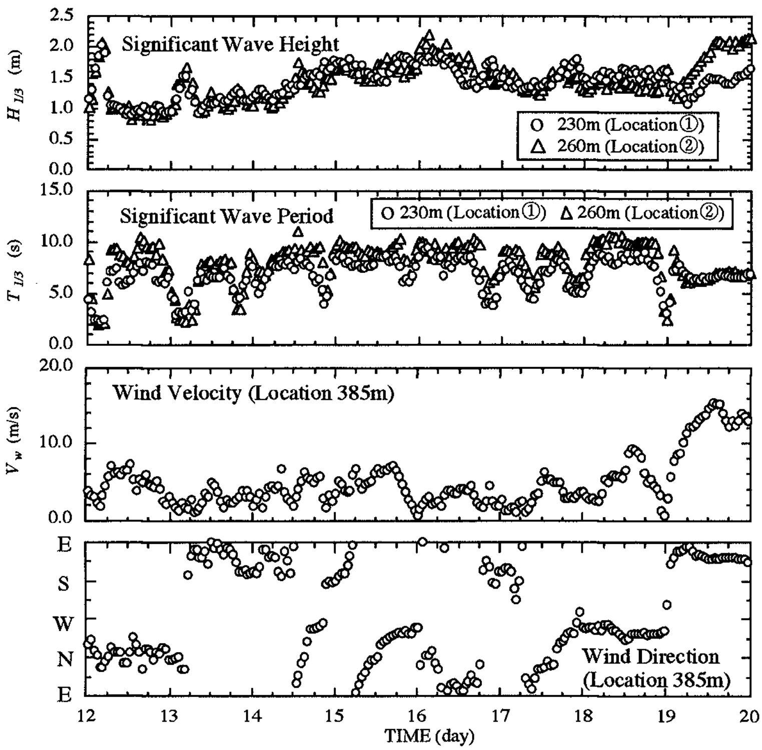

FIG. 7. SIGNIFICANT WAVE HEIGHT AND PERIOD, AND WIND INFORMATION (50 MINUTES-LONG AVERAGED DATA)

Response of Stress in Sand to Wave Action

To compare the stress condition in the sand with the wave condition, the stress data were also processed in the same way as the waves were. Figure 8 illustrates the time histories of the significant pressure, stresses and velocity data. The pressure data can be linearly converted to the sea surface elevation. It is seen that the amplitude of the effective stress change in one wave period becomes larger with the significant wave height. It implies that the effective stress is directly controlled by the wave action.

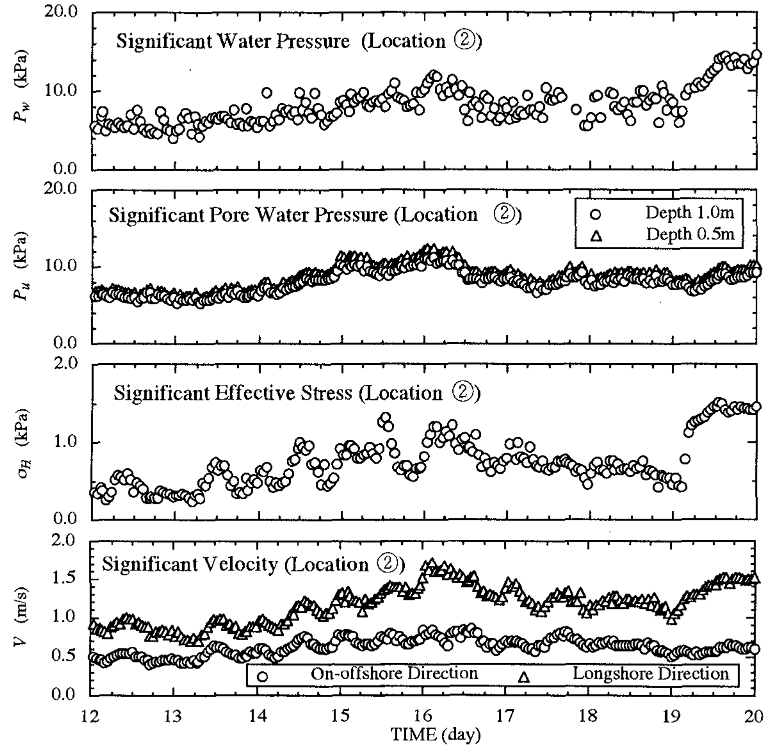

FIG. 8. SIGNIFICANT STRESS AND VELOCITY (50 MINUTES-LONG AVERAGED DATA)

The averaged data are shown in Figure 9. There is a sharp depression everyday in the effective stress data, and it becomes larger with time until 17th. The pore pressure exhibits the similar response but in the positive direction. Then adding them together makes the variation at the time become negligible. It is also seen that the drop in the averaged effective stress occurs at the lowest elevation of the sea surface in each day. Clear cause for these events are not understood, but the non-linearity associated with shallower water depth may be attributed. Correlation with the wave height is not clear either, since high waves came from 15th evening to 16th morning.

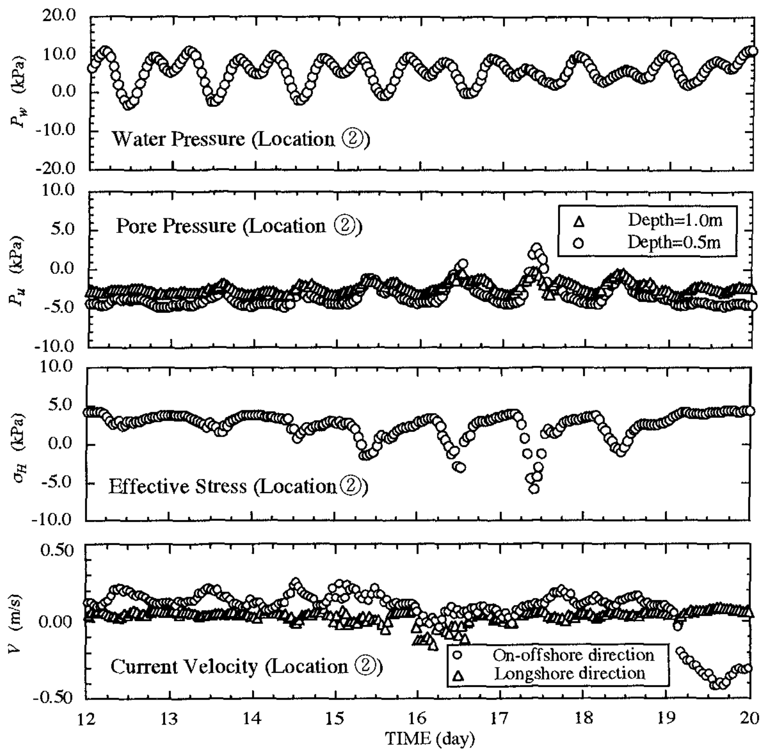

FIG. 9. 50 MINUTES-LONG AVERAGED STRESS AND VELOCITY

Bottom Elevation Change

It is reasonable to assume that the effective stress represents the thickness of the sand above. Then, the vertical location of the effective stress sensor in relation to the sea bottom can be estimated by the following equation (1), and consequently the sea bottom elevation, Δh is evaluated.

$$\Delta h = \frac{\sigma_H}{K_0\{(1-n)(\rho_s-\rho_w)g\}} \qquad (1)$$

where K_0, n, ρ_s, ρ_w and g are coefficient of earth pressure at rest, porosity, density of soil particle, density of sea water and gravity acceleration. The averaged effective stress, σ_H was used in the equation. Note that since there are large drops in the averaged effective stress series as mentioned above, those data was unconsidered. If these data were converted to the thickness based on equation (1), it turned out to be about 3 m depth change, which is unrealistic. The effective stress change is assumed to be solely by the change of sand layer thickness in equation (1), and those large stress drops are more likely to be caused by other physical factors.

The estimated sea bottom elevation is shown in Figure 10 along with the measured elevation. The estimate appears to oscillate about the measurement. But, considering that the measurement was made only once a day and that the elevation possibly changes within a day, the estimated changes are compared well with the measured data at the corresponding time. This trend is observed both at location 1 and at location 2. Agreement between the measured elevation and the estimate by the effective stress implies that the effective stress is directly related to the sand movement and the sea bed elevation change can be estimated from the information on the effective stress. From this point of view the effective stress sensor employed in this study is found to be one of the most efficient instrument to provide the information on the sediment movement. It also suggests that the bottom elevation may fluctuate in a day and may have to be measured more than once in such a day to understand the actual movement.

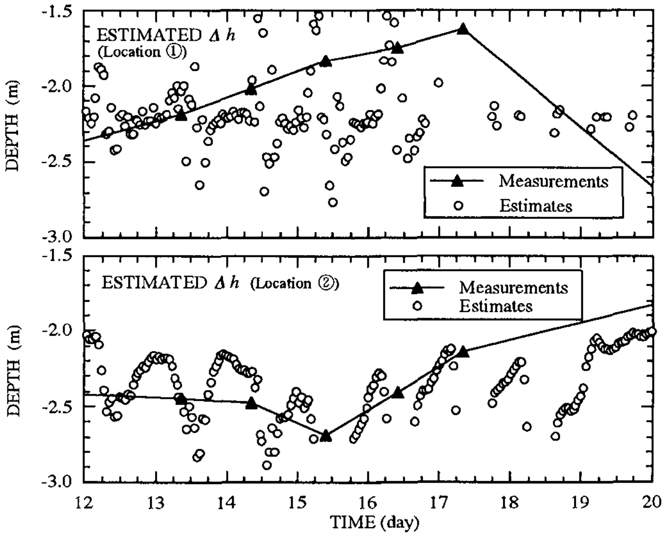

FIG. 10. ELEVATION OF BOTTOM SURFACE

Effect of Ground Water

There are some studies indicating connection between ground water and sediment transport (*e.g.*, Grant, 1948). Since the ground water level near the shoreline was continuously measured by Port and Harbour Researeh Institute, its effect was attempted to examine. The sea surface level and ground water table changes are compared in Figure 11. There is a long-period variation in the time history of the ground water level, which is similar to the wave height record in the same period; *i.e.*, the ground water level rose as the wave became higher. There is also oscillations with short periods, responding to the tides. Thus, it is clear that the ground water near the shore is influenced by the sea conditions.

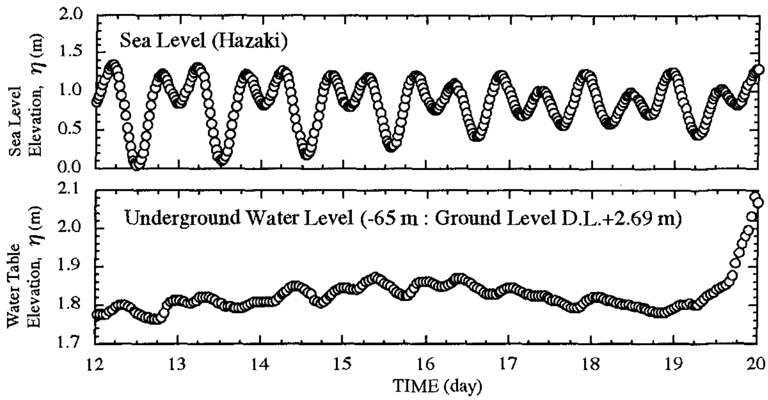

FIG. 11. SEA LEVEL AND WATER TABLE ELEVATIONS

Further, this rise and drop of the ground water level due to the sea condition change may affect the stress condition in the sand bed in the surf zone. Especially, the liquefaction and the sand movement on a bar may be affected by the ground water, because rapid pressure change at bottom by surface wave may cause the discontinuity between that pressure and the pressure defined by ground water.

Effects of Non-Linearity

To examine the non-linear effects of the surface waves on the effective stress, skewness and kurtosis were calculated from the measured sea surface elevation data. When those values in Figure 12 are compared with the time histories of the wave height and effective stress, the skewness becomes slightly bigger with the wave height and the kurtosis remains constant. From these observations clear relation between the non-linearity of the surface waves and the effective stress is not recognized.

Effects of Long-Period Component of Waves

From the spectrum computed from the sea surface data, the long period waves are estimated and shown in Figure 13. In this study, only the components with the period longer than 30 s are picked. The long-period wave had larger height on 15 th and 16th, the duration of which coincides with that of the higher significant wave. The trend of long-period wave height is also found in the time history of the ground water level. It implies that the ground water near the coast can be affected by the longer waves.

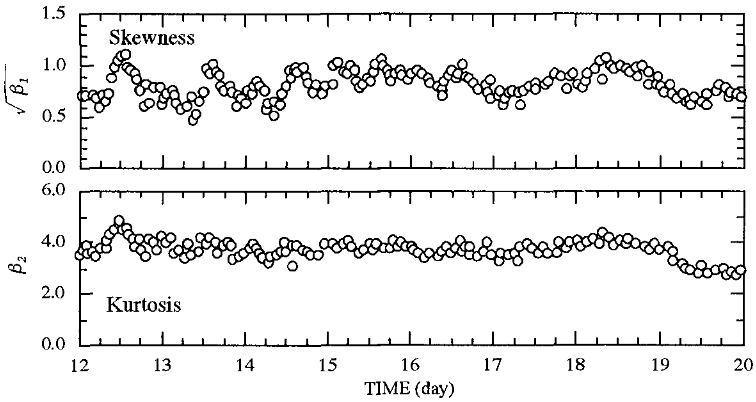

FIG. 12. EFFECTS OF NON-LINEARITY

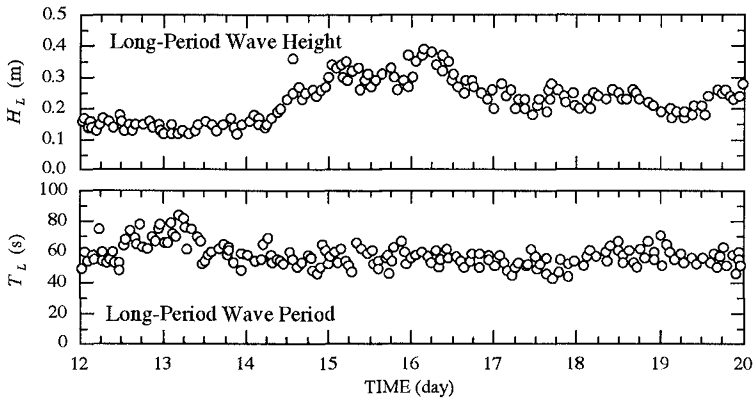

FIG. 13. EFFECTS OF LONG-PERIOD WAVES

Relation between Stresses and Wave Steepness

Using the significant wave height and period, and the corresponding effective stress change, their relation is examined in Figure 14, which exhibits the strong linear relation between them.

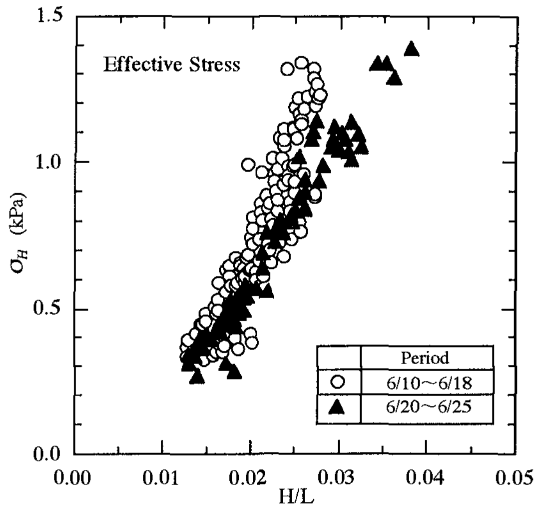

FIG. 14. CORRELATION BETWEEN EFFECTIVE STRESS AND WAVE STEEPNESS

CONCLUSIONS

The effective stress and pore pressure in the surf zone were directly measured to study the relation with the stress, and the wave condition and other factors, and to evaluate the bottom elevation change from the effective stress data. Though the data were collected only 10 days because of difficult installation of the instruments in the surf zone and the damage by high waves, there were two moderate storms in the measuring period. From the careful observation and analysis of the measured data during this period the followings are found.

(1) The pore pressure and effective stress appears to respond to the water surface elevation without any time lag. The measured area is always attacked by breaking waves and the sand there is anticipated to be loose. Then, the pressure on the bottom transmits almost simultaneously to the pore pressure inside the soil.

(2) The mechanism of liquefaction in the surf zone seems to be different from that outside the surf zone. The large effective stress drop and strong flow in the onshore direction when the wave crest passes are the possible cause for the sand movement in the surf zone.

(3) The water depth change estimated from the effective stress records agrees well with the measured depth change. This leads to the following three conclusions.

(a)The effective stress in sea bed is closely related to liquidization of sand and then to sand movement.

(b)The sea bottom elevation change can be evaluated from the effective stress in the sand and equation (1).

(c)The cffective stress sensor was proved to be useful in estimating local and temporal sediment transport.

(4) Both the pore pressure and effective stress show larger variation when the short waves with large wave steepness pass.

(5) The currents going offshore were observed when thc sea level was low. The effective stress varied corresponding to these currents.

(6) The averaged effective stress over 50 minutes drops sharply at low tide. The shallower water depth may be a possible cause, and the exact reason for this is still being studicd.

(7) The ground water level near the coast is likely to affected by the long waves and tidal changes.

ACKNOWLEDGMENTS

The writers gratefully acknowledge the Port and Harbour Research Institute, Ministry of Transport, Japan, for permission to use the observation pier of Hazaki Oceanographical Research Facility.

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