CHAPTER 7

Field Observation on Wave Set-up near the Shoreline

Shin-ichi YANAGISHIMA[1] and Kazumasa KATOH[2]

Abstract

To understand the actual condition of the abnormal rise of sea water on the beach in a storm, the field observation has been carried out at Hazaki Oceanographical Research Facility for about one year under the comprehensive conditions. The relation between the sea level rising and the external forces such as waves, deviations of atmospheric pressure and the winds are examined. The contribution of the wave set-up on the sea level rising is large, while those of the atmospheric pressure and the wind are small. The observed wave set-up near the shoreline agrees well with the predicted value by the Goda's theory. There are other factors which slightly affect the sea level changing, that is to say, a time lag behind the storm, the ocean currents, and the wave steepness.

1. Introduction

Since the sea level rising near the shoreline is considered to be strongly related to the beach erosion in a storm, it is important for predicting the changes of beach and for developing more reliable shore protection technique to estimate the precise result of sea level rising in the field.

The incident wave raises the sea level in the surf zone, that is the wave set-up. The mechanism of wave set-up has been already theoretically explained by introducing the concept of radiation stress (Longuet-Higgins and Stewart, 1962). It has been experimentally proved in the laboratory, for example by Bowen, Inman and Simmons(1968). The wave set-up on the complicated beach topography could

[1]Littoral Drift Lab., Port and Harbour Research Institute, Nagase 3-1-1, Yokosuka, Kanagawa, Japan

[2]Chief of Littoral Drift Lab., Port and Harbour Research Institute

be also calculated by using a electric computer. So far, several fields observation on the wave set-up have been done (eg., Hansen, 1978; Holman, 1986). They were, however, not sufficient to verify the predicted wave set-up by these method.

On the actual beach, in addition to the wave set-up, the wind and the depression of atmospheric pressure have also the effects on sea level rising in a storm.

In this study, the field observation has been carried out at Hazaki Oceanographical Research Facility (HORF) for about one year to understand the actual sea level rising near the shoreline and to examine the theory of wave set-up by using the field data.

2. Field Observation

The site of the field observation is a entirely natural sandy beach, being exposed to the full wave energy of the Pacific Ocean, and is classified as micro tidal beach with the tide range of about 1.4 meters (see Figure 1). On this beach, Port and Harbour Research Institute, Ministry of Transport, has constructed the Hazaki Oceanographical Research Facility (HORF) in 1986 for carrying out the field observation in the surf zone even under sever sea conditions. The research pier is a 427 meters long concrete structure. It is supported by 0.8 meter diameter concrete-filled steel piles in a single line, at 15 meters interval. The pier deck is 2.5 meters wide and 7 meters above L.W.L. In this facility, the field observation on the wave set-up had been carried out near the shoreline for about one year from 14 January to 2 December in 1987.

In Figure 2, although many instruments are permanently installed along the research pier, only the locations of

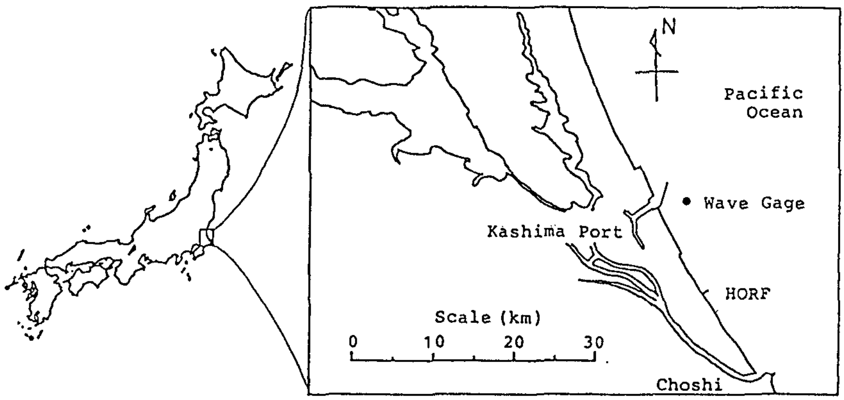

Figure 1 Site of field observation

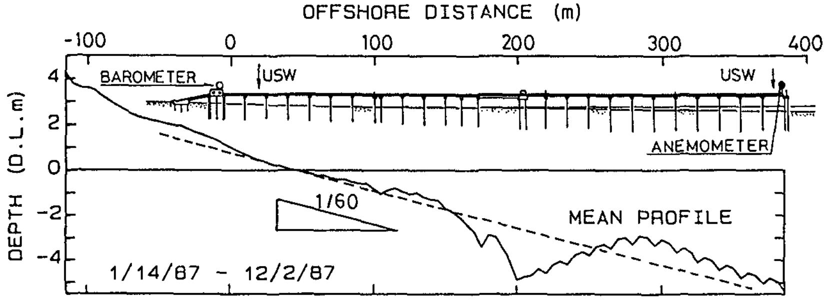

Figure 2 Locations of instruments

instruments used in this study are shown.

In order to measure the mean sea level at the shoreline with a good precision, it is necessary to measure the wave run-up and down on the beach by the tedious technique such as taking pictures by using 16 mm motion-picture camera (Holman, 1986). It is, however, very difficult to measure the mean sea level by this method for a long time, which will be the main cause of losing the chance to measure the most desirable situation in a storm. Furthermore, this method will take much time to analyze the many films. Then, an ultrasonic wave gauge was installed to the pier deck at the reference point +22m (see Figure 2 and 3). The latitude of installation was 6 meters above the mean water level. The mean grand level at the observation point was 0.3 meter above the datum line. The mean water depth was about 0.4 meter in M.W.L. Since the observation point was fixed, its relative position from the shoreline changed with time due to the change of tide level. The measurement had been done during 20 minutes of every two hours with the sampling interval of 0.3 second.

The wind direction and velocity was measured at the tip of research pier by using the two-component type ultrasonic anemometer. The installed latitude of anemometer was 10 meters above the mean water level. The atmospheric pressure was measured in the laboratory by using a barometer. These measurements had been also carried out every two hours.

The measurements described above were automatically controlled by using a mini-computer in the laboratory at the base of research pier.

The offshore waves have been measured at the mean water depth of 23.4 meters near the Kashima Port (see Figure 1). This measurement

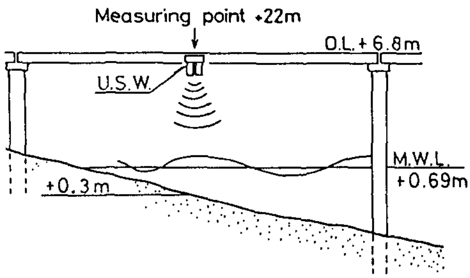

Figure 3 Ultrasonic wave gauge

has been also done during 20 minutes of every two hours.

The beach profile along the research pier was surveyed with a lead from the pier deck. The profile of the backshore and the foreshore was surveyed by using a surveyor's staff and a transit. The cross-shore interval of these measurements was 5 meters. The measurements had been done, once a day except on Sunday and on the national holiday, by the researchers stayed in the HORF. The mean profile during the observation which is calculated with these data is shown in Figure 2.

3. General conditions during Observation

Photo. 1 is the side view of HORF which was taken under a calm condition when we could easily come out from the HORF on foot on the beach. On the other hand, Photo. 2 was taken in a storm wave condition. The facility was isolated since the sea level rose and also the long period wave became larger near the shoreline. In connection with the long period waves in this area, Katoh and Yanagishima(1990) examined the berm erosion in the storm.

Data set of 1305 obtained in these measurements are utilized in analyses. In this chapter, based on these data, the general conditions of sea and whether during the observation are described.

Figure 4 shows the frequency distribution of offshore wave heights which distribute in the range from 0.4 meter to 6.4 meters. The highest frequency is in the rank of 1 to 1.5 meters. There are 91 sets of data containing the storm waves, in which the wave heights are greater than 3.0 meters. Figure 5 is the frequency distribution of the

Photo. 1 HORF (Calm condition)

Photo.2 Isolated HORF (in a storm)

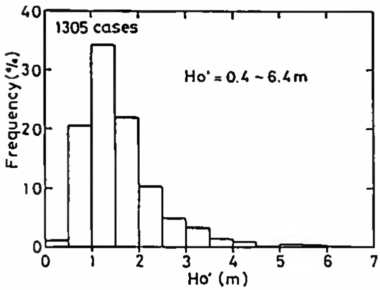

Figure 4 Frequency of off-shore wave height

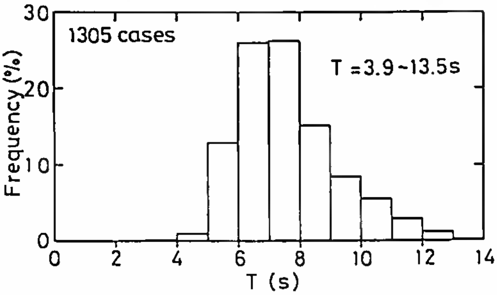

Figure 5 Frequenfy of period

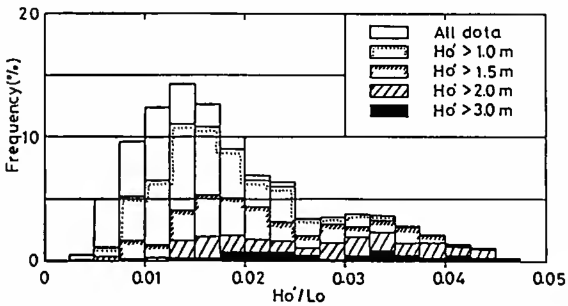

Figure 6 Frequency of steepness

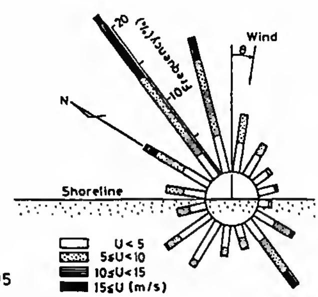

Figure 7 Frequency of wind

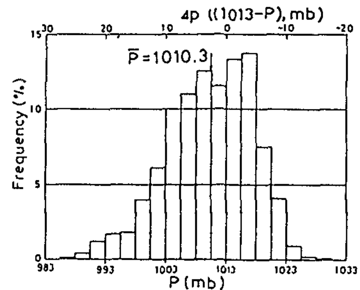

Figure 8 Frequency of atmospheric pressure

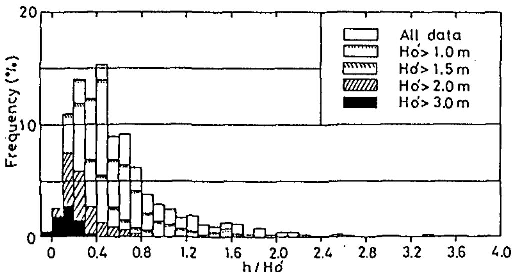

Figure 9 frequency of water depth

offshore significant wave periods during about one year observation. The periods distribute in the wide range from 3.9 seconds to 13.5 seconds, being about 7.6 seconds in average.

Figure 6 shows the combined distribution of significant wave heights and periods, that is, the wave steepness. The high waves greater than 2 meters have two modes at about 0.015 and 0.032 in the steepness. The former is corresponding to the swells, and the latter is to the wind waves.

Figure 7 shows the wind rose by distinguishing the rank of wind velocities which range from 0.6 to 19.8 m/s. The symbol θ in this figure is a wind direction defined in the later analysis.

Figure 8 is a frequency distribution of atmospheric pressures which range from 987 to 1030 mb, being about 1010 mb in average. On the upper abscissa, the deviation of atmospheric pressures from 1013 mb is also shown.

Figure 9 is the frequency distribution of non-dimensional water depth at the observation point. The mode for all data is at about 0.2 to 0.5, while it is at about 0.1 to 0.2 for the offshore waves greater than 2 meters.

As we have seen so far, the field observation of sea level rising near the shoreline had been carried out under the comprehensive sea and whether conditions.

4. Data Analyses on Wave Set-up

The mean sea water level near the shoreline was estimated by calculating the mean value of the wave profile data measured at the reference point +22m. The mean water depth during the each measurement period of 20 minutes can be estimated with the daily beach profile data. The case that the mean water depth is less than 50 cm has never been included in the total number of available data sets of 1305, since the bottom at the observation point occasionally emerged when the swash run down in this situation.

In order to evaluate the rate of sea level rising, it is

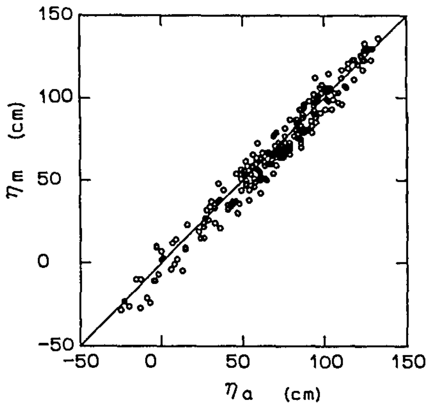

Figure 10 Comparison of astronomical tide level with mean sea level at a tip of pier

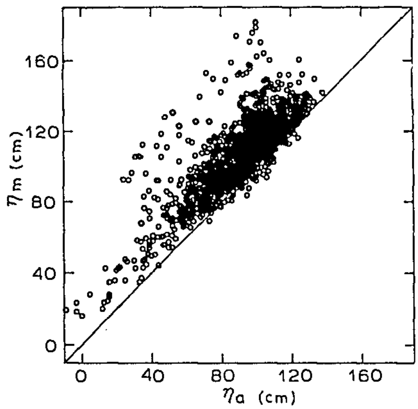

Figure 11 Relation between still water level and measured water level

necessary to know the still water level. In the laboratory, it is easy to measure it by stopping the wave generator. It is, however, impossible to control the wave characteristics in the field. One method to estimate the still water level is to measure the offshore sea level where there is no wave set-up due to the waves. There was, however, no facility to measure it in the offshore. The mean water level measured at the tip of research pier is not considered as the still water level, because the research pier is located entirely inside the surf zone when the large waves came to the site. Then, the astronomical tide levels at the site were calculated by composing 40 tidal constituents which is the result of harmonic analysis with the tide data obtained in the Kashima Port, to consider it as the still water level.

Figure 10 is the comparison of the predicted astronomical tide level on an abscissa with the mean sea level measured at the tip of research pier on an ordinate. In this comparison, only the cases which satisfy the following conditions simultaneously are plotted, that is to say; the significant wave height was less than 1 meter, under which the tip of pier was located far offshore from the surf zone; the absolute deviation of atmospheric pressure was less than 5 mb; the wind velocity was less than 3 m/s. There is a good agreement between them in Figure 10 which encourage us to consider the predicted tide level as the still water level.

In Figure 11, the measured mean sea levels near the shoreline are plotted on an ordinate against the predicted still water level on an abscissa for 1305 cases. Almost all of the measured sea levels are higher than the still levels. In short, there were usually some amount of sea level rising.

Figure 12 shows the changes of offshore wave heights, atmospheric pressures, wind velocities and the sea levels in the storm due to the typhoon in september, 1987. In the lowest figure, the solid line is the predicted still water level and the plotted data are the measured mean sea levels. When the measured sea level was maximum, being about 80 cm higher than the still water level, the offshore wave height was maximum; the atmospheric pressure was minimum; and the wind velocity was maximum. That is to say, the sea level rising depends on not only the incident waves but also the deviation of atmospheric pressure and the wind velocity. Therefore, to examine the wave set-up with the field data, we must take these factors into account at the same time in the analysis as follow;

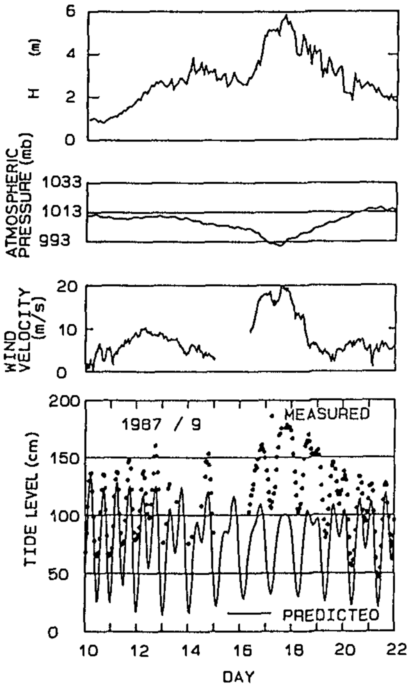

Figure 12 Sea level rising due to typhoon in 1987

$$\eta = f_1(\text{wave}) + f_2(\text{atmo. pressure}) + f_3(\text{wind}). \quad (1)$$

Concerning to the wave set-up due to the incident waves, the theoretical treatments had been developed since Longuet-Higgins and Stewart (1962) introduced the concept of radiation stress. In the early stage, the rate of wave set-up was expressed by only the wave height. In contrast to this, Goda(1975) theoretically investigated the effects of the beach slope and the offshore wave steepness on the wave set-up, based on his model of the random wave deformation in the surf zone.

Figure 13 shows the Goda's theory on the wave set-up for the sea bottom slopes of 1/50 and 1/100, by taking the non-dimensional wave set-up at the shoreline normalized by the offshore wave height on an ordinate and the offshore wave steepness on an abscissa. To introduce his theory into the

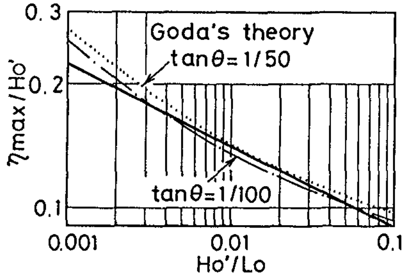

Figure 13 Goda's theory on wave set-up

analyses, let's inspect the natural conditions. The mean sea bottom slope at the observation site is about 1/60 as shown in Figure 2. The value of wave steepness distributes in the range from 0.005 to 0.047 for all wave data, and in the range from 0.01 to 0.047 for the waves greater than 2 meters in height as shown in Figure 6. Therefore, in this scope of conditions, the Goda's theory can be approximated by the straight line in the Figure 13. Taking only the inclination of this line into account, we have

$$f_1(\text{wave})/Ho' = a\ (Ho'/Lo)^{-0.2}, \tag{2}$$

where a is a coefficient, Ho' and Lo are the offshore wave height and wave length respectively.

As the deviation of atmospheric pressure, ΔP, induces the statistical rising of sea level, let's assume the following proportional relation between them;

$$f_2(\text{atmo. pressure}) = b\ \Delta P\ , \tag{3}$$

where b is a coefficient.

Since the shear stress exerted by wind on sea surface is proportional to the square of wind velocity, the relation

$$f_3(\text{wind}) = c\ U^2\cos\theta \tag{4}$$

is usually assumed, where c is a coefficient, U is the wind velocity at the altitude of 10 meters above the sea surface, and θ is the wind direction (see Figure 7).

By substituting Eqs.(2), (3), and (4) into Eq.(1) and adding one more coefficient C, we have

$$\eta = a(Ho'^2 Lo^{1/2})^{0.4} + b\Delta P + cU^2\cos\theta + C\ . \tag{5}$$

The physical units of the term in Eq.(5) follow the general customs, that is, cm for η , mb for ΔP , m/s for U, and m for Ho' and Lo.

Using the multiple regression analysis with 1305 sets of data, we decided the values of four coefficients as follows;

$$a=5.20(\text{cm/m}), b=0.69(\text{cm/mb}), c=0.04(\text{cm/m}^2/\text{s}^2), C=-4.85(\text{cm}). \tag{6}$$

By using Eq.(5) with the coefficients in Eq.(6), the total sea level risings have been calculated for 1305 cases. Furthermore, to have mean sea level, the predicted still water level (astronomical tide level) has been added to every total sea level rising. Figure 14 is a comparison of the measured sea level with the calculated one, by taking the abscissa for the calculated values. There is a close agreement between measured and calculated values, excepting that the measured sea levels are slightly higher than calculated one when the sea levels are low.

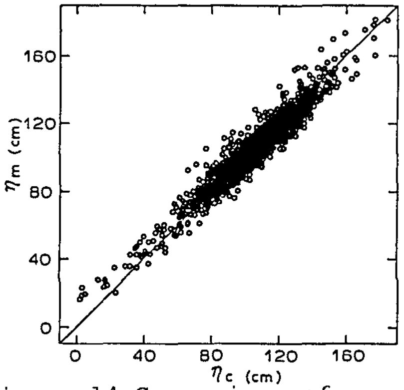

Figure 14 Comparison of measured sea level with calculated one

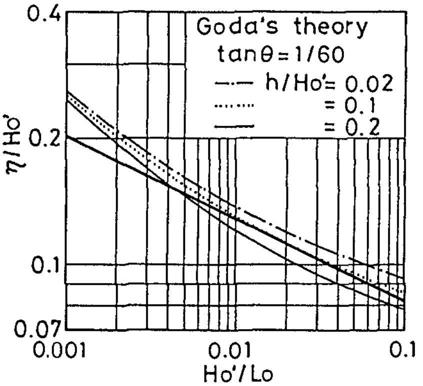

Figure 15 Comparison of Eq.(8) with Goda's theory

The exception is due to the reason that the observation point was shifted relatively to the onshore-side when the sea level was low, which induced the higher rate of wave set-up.

Now we have the empirical relation between the wave set-up and the wave characteristics, that is,

$$\eta_{wave} = 0.052(Ho'^2Lo^{1/2})^{0.4}, \tag{7}$$

or

$$\eta_{wave}/Ho' = 0.052(Ho'/Lo)^{-0.2}, \tag{8}$$

where η_{wave} is the rate of wave set-up near the shoreline. Please pay attention to the physical unit in these expression, that is to say, in meter.

Let's compare Eq.(8) with the Goda's theory in Figure 15. The solid straight line is Eq.(8). The three curved lines are the Goda's theory for the wave set-up rate at the non-dimensional water depth of 0.02, 0.1 and 0.2 respectively on the beach sloping of 1/60. In the storm, the range of non-dimensional water depth at the observation point was from 0.1 to 0.2 as shown in Figure 10, and the wave steepness distributes in the range from 0.01 to 0.047 as shown in Figure 6. Considering these conditions, there is a well agreement between Eq.(8) and the Goda's theory.

The interesting modification can be done by substituting the energy flux of incident wave in the offshore,

$$E_f = (\omega o/)(g/2\pi)^{1/2}Ho'^2Lo^{1/2}, \tag{9}$$

into Eq.(7), where E_f is the wave energy flux and ωo is the density of sea water. In short, the rate of wave set-up near the shoreline can be expressed with the incident wave energy flux,

$$\eta_{wave} = 0.14\ E_f. \qquad (10)$$

Based on the empirical relation obtained, the contribution of each factor on the sea level rising has been estimated for 1305 cases and shown in Figure 16. For example, the level rising of about 80 cm occurred in eleven cases, in which the averaged wave set-up rate is 57 cm, the level rising due to the wind is about 9 cm, and that due to the atmospheric pressure is about 14 cm. According to this figure, the contribution of the wave set-up is predominant, which occupies about 75% portion of the total sea level rising.

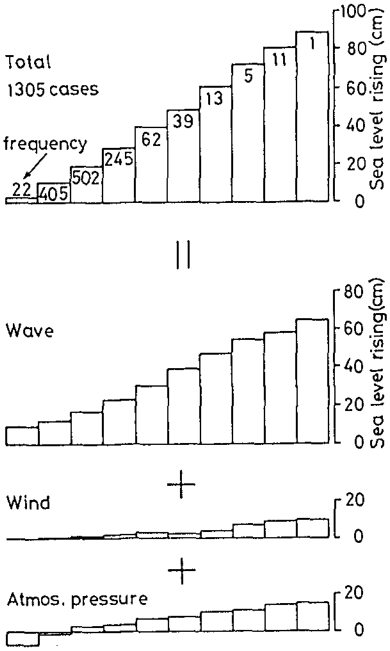

Figure 16 Contibution of wave on wave set-up

5. Contribution of Other Factors on Sea Level Rising

So far, to explain the sea level rising, the waves, the atmospheric pressures, and the winds have been considered as the external forces in the regression analysis. As the result, the real sea level rising have been practically explained by these three factors as shown in Figure 14. There are, however, a little scatter in the plotted data in Figure 14, which may be due to not only the errors in measurements but also the other factors we did not considered. Figure 17 shows the difference between the measured sea levels and the calculated ones in a time series. If the measured and the calculated ones agree precisely, the data should lie in a zero line. The plotted

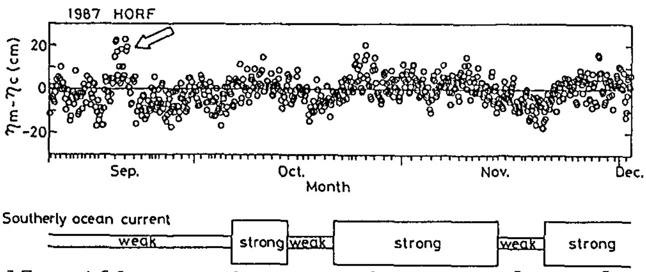

Figure 17 Difference between the mesured sea levels and calculated ones in a time series

data, however, scatter around the line. According to this figure, three items can be pointed out.

First, the data are scattered in a belt of about 15 cm in width. Although the observation point was fixed, the distance from the shoreline to the observation point changed with time since the shoreline position changed with the tide level, yielding the change of wave set-up rate. The tidal range in the site is about 1.4 meters, which introduces the fluctuation of about 13 cm in the wave set-up rate, according to the Goda's theory (see, Katoh et al., 1989). Therefore, it is considered that the data scattering in the belt is mainly due to the change of tide level.

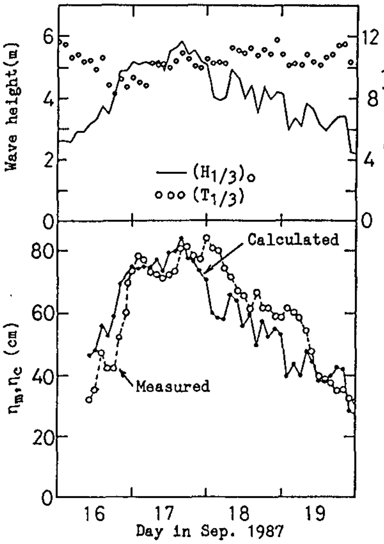

Figure 18 Time lag between measured set-up and calculated one

Secondly, there is a large difference between the measured sea levels and the calculated ones, which is denoted by an arrow in Figure 17. In order to investigate the cause of it, it is necessary to inspect more precise data during these days. Figure 18 shows the changes of offshore wave height, wave period, and the measured and the calculated sea level rising during the corresponding days. The measured and the calculated rising change in the similar manner. There is, however, the time lag between them. That is to say, the change of actual sea level rising is 2 to 3 hours behind the calculated one in both the development and decrement of incident waves during the storm, which introduces the large difference on the day denoted by the arrow in Figure 17.

Thirdly, the belt, in which the plotted data are scattered, fluctuates with a period of about one month. To investigate this cause, the ocean currents must be considered since two ocean currents from the north (Oyashio) and from the south (Kuroshio) come across in the offshore area just in front of the observation site. When the Oyashio, the southerly ocean current, is relatively stronger as shown in Figure 19, the Corioli's force due to this current should raise the sea level near the coast. Then, we have inspected the weekly averaged patterns of these currents which are issued by Ibaraki Prefectural Fisheries Experimental Station every week (Figure 19 is an example). The strength of southerly ocean currents have been decided and shown in the lower in Figure

17. During the period when the southerly ocean current was strong, the measured sea levels were higher than the predicted ones, and vice versa. Then, it can be said that the long period fluctuation of the difference between the measured sea levels and the predicted ones are due to the changes of the Corioli's force which depends on the strength of southerly ocean current.

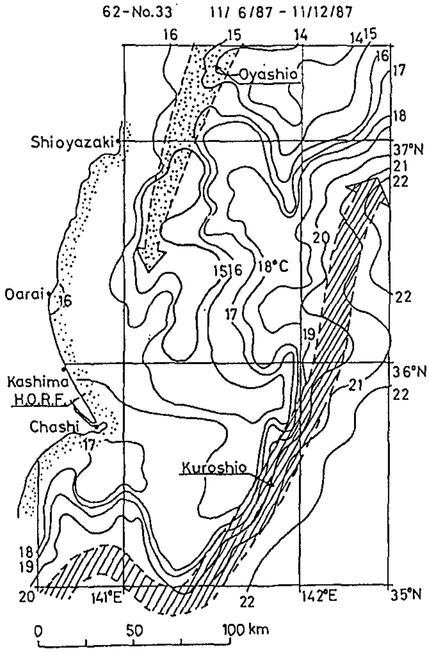

Figure 19 Pattern of ocean currents

Next, the dependency of wave set-up on the offshore wave steepness will be examined. According to the Goda's theory, the wave set-up depends also on the offshore wave steepness. In order to confirm this dependency, we had selected the data which satisfy the following three criteria at the same time.

(a) The offshore significant wave height is greater than 2 meters.

(b) The non-dimensional water depth, h/Ho', is less than 0.2, which is a condition to select the data measured close to the shoreline.

(c) The absolute difference between the measured sea level and the predicted one is less than 5 cm, which is a condition to omit the data containing the unknown effects in it.

Figure 20 shows the comparison of the selected data with

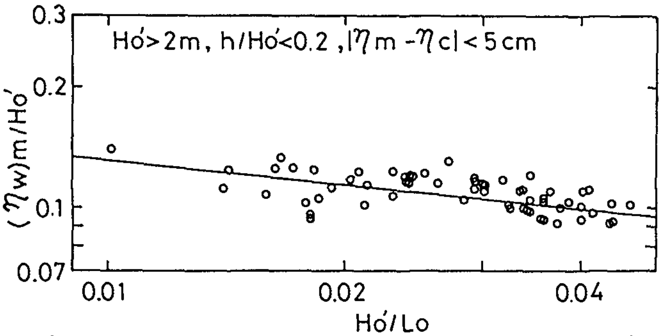

Figure 20 Effect of wave steepness on wave set-up

the Goda's theory which is the straight line in the figure. The rate of wave set-up weakly depends on the offshore wave steepness. The non-dimensional wave set-up becomes to be slightly larger with decreasing of the wave steepness.

The dependency of wave set-up on the incident wave angle to the beach have not been examined, since the wave direction had not been measured.

6. Conclusions

The conclusions obtained in this study are as follows:
(1) The wave set-up measured near the shoreline in the field strongly supports the Goda's theory.
(2) The rate of wave set-up, which becomes to be larger with decreasing of the wave steepness, can be expressed with the incident wave energy in stead of wave height.
(3) In total sea level rising, the contribution of the wave set-up is large, which occupies about 75% portion, while those of depression of atmospheric pressure and the winds are small.
(4) There are other factors which slightly affect the sea level changing as follows:
  a. The actual sea level rising (or changing) is 2 to 3 hours behind the development and decrement of incident waves during the storm.
  b. The strength of ocean current velocity in Oyashio in the offshore area induces the sea level changing with the period of about one month.

References

Bowen,A.J., D.L.Inman and V.P.Simmons (1968):Wave 'set-down' and set-up, Jour. of Geoph. Res., Vol.73, No.8, pp.2569-2577.

Goda,Y.(1975):Deformation of irregular waves due to depth-controlled wave breaking, Rep. of PHRI, Vol.14, No.3, pp.59-106 (in Japanese, see Goda,1985).

Goda,Y.(1985):Random seas and design of maritime structures, University of Tokyo Press, 323p.

Hansen,U.A.(1978):Wave setup and design water level,Jour. of Waterway Port and Ocean Div., ASCE, Vol.104, WW2, pp.227-240.

Holman,R.A.(1986):Extreme value statistics for wave run-up on a natural beach, Coastal Engineering, Vol.9, pp.527-544.

Katoh,K. et al.(1989):Wave set-up near the shoreline, Rep. of PHRI, Vol.28, No.1, pp.3-41 (in Japanese).

Katoh,K. and S.Yanagishima (1990):Berm erosion due to long period waves, Proc. of 22nd ICCE.

Longuet-Higgins, M.S. and R.W. Stewart (1962):Radiation stress and mass transport in gravity waves, with application to 'surf beat', Jour. of Fluid Mech., 13, pp.481-504.