CHAPTER 57

BORE-LIKE SURF BEAT ON REEF COASTS

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Abstract

Reef coasts, because the wave height of incoming stormy high waves are extremely dampened by coral reef, have been believed as calm sea areas. However, many coastal structures have actually been damaged by stormy waves dampened by the reef. Surf beat with large wave height was discovered through field observations. The surf beat has been named as "Bore-like Surf Beat". The wave height and the wave velocity of the Bore-like surf beat is lager than that of individual waves. Numerical simulation taking into account of non-linear effect of surf beat phenomenon on the reef shows good agreement with laboratory data.

The main reason of the disasters of coastal structures on the reef coasts is existence of the Bore-like surf beat resonantly excited incoming wave groups.

Introduction

The coasts around the Southwest Islands of Japan are what is called the reef coast, which is surrounded by natural coral reef. On the reef coasts, the sea area is made comparatively calm due to the energy dissipating effect of the reef to the incoming waves, as the natural submerged breakwater. Therefore, it has been believed that the existence of the reef is contributed for the safety of the coastal structures. But actually, disasters caused by Typhoon waves have frequently occurred on reef coasts and is contradictory to the general concept that " the reef coast is a calm sea area ".

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Since 1973, the waves on reef coasts have been investigated by Kohno and Tsukayama. They mainly clarified the wave deformation on the reef by laboratory experiments and/or field observations. Takayama et al. (1977) experimentally investigated the waves on the reef with irregular waves, and proposed a empirical estimating formula for the wave height and wave set-up on the reef. After Takayama et al., the estimating formula of the wave height on the reef has usually been used in design for coastal structures in reef coasts of the Southwest Islands of Japan. The wave height expected by Takayama's empirical equation gives about 1m for incoming waves with the wave height above 10m. As for the wave set-up, it is about 1.5m. In the traditional design concept, as generally speaking, the reef area is one of the calm sea.

Surf beat phenomena on the reef were discussed by Seelig(1983). He firstly shown that the surf beat contributes the wave run-up. But no characteristic of surf beat is clarified.

Recently, Tsukayama and Nakaza clarified the wave deformation due to the large roughness of the coral reef as well as the wave breaking deformation.

There are many study on the individual waves in sea areas with the reef, as shown above. But the surf beat on the reef coasts has not been studied enough. In this paper, first of all, the actual condition of wave disasters on the reef coasts is shown, and then it is disclosed that the main reason of the sever coastal disasters is the existence of surf beat with the wave height larger than one of individual waves. Secondly, the surf beat phenomena resonantly excited by incoming wave groups on the reef are shown by field observation data as well as experimental and numerical ones.

2. What happened on reef coasts ?

(i) A typical topography of the reef coasts in the Okinawa Islands of Japan, and waves on there

Figure-1 shows a topography of typical reef coast of the Okinawa Islands in Japan. It may be the same type as the reef in Australia, which is well known as the Grate Barrier Reef. The width of the reef is about 300m to 1000m, and the water depth at high tide is about 2m to 3m. The heel of the beach is called as beach front, and the offshore edge of the reef flat is called as reef front. As shown in Fig.-1, many coral reef of the Okinawa Islands have a steep slope, which is about 1/10 in front of the reef flat. In some cases, the offshore side of the reef flat edge become more sharply sloped.

Photograph-1 shows the wave condition on the reef when the deep water wave height is about 4m. As shown in this photograph, the incoming waves are rapidly dampened. Therefore, the wave height on the reef is extremely small, except near the reef front. For example, as seen in photo.-1(b), near the shore line, a child can play with the waves, for its height is very small.

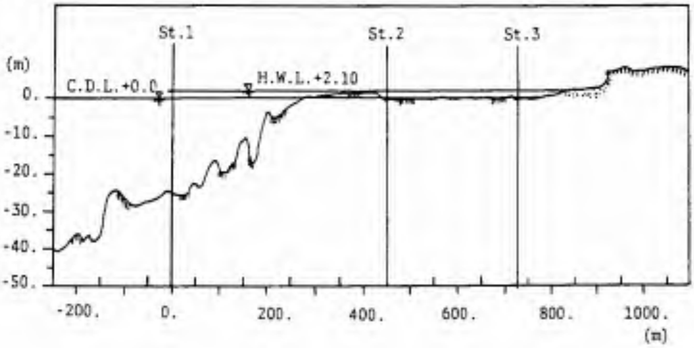


Fig. 1 Cross-sectional topography of a typical reef coast of Okinawa Islands in Japan

(a) Wave braking near the reef front

(b) waves near the shore line

Photo.-1 waves on a reef coast under a Typhoon condition

In Okinawa Islands, the coastal structures have usually been constructed in the reef zone. Existence of a coral reef has been believed that it acts as safety guard for coastal structures against incoming high waves. Because the water depth on the reef is about 2m, and it has a wide breaking zone which perfectly reduces the height of incoming waves.

(ii) Damages of coastal structures by stormy high waves due to Typhoon

The results of recent surveys of coastal disasters on the reef have shown that many coastal structures severely been destroyed. These disasters are due to extremely high storm surges (flood-like waves) which are higher than 5.0m above Datum Level.

Photograph-2 shows a seawall, roads, and houses damaged by a typhoon. The elevation of foundations of the houses and roads is between 5.5m and 7m above the high water level. And the elevation of seawall crown near the shore line is 5.5m above the high water level.

Figure-2 shows a sketch drawn by three civil engineers who happened to have been there during that typhoon disaster. They explained the disaster as follows.

Photo.-2 Destroyed seawall and road due to storm surges (Sosu coast, Typhoon T8613)

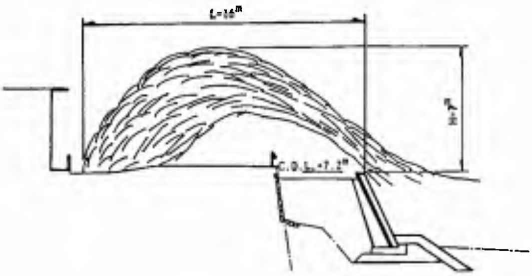


Fig.-2 Sketch of an overtopping wave

The damage was caused by big floods, meaning stormy surges. The big floods surged on the seawall and overtopped it at about 10-minutes intervals (as will be shown, which corresponds to the natural period of the reef coast).

From the traditional estimating method, the wave set-up for a 10m wave in deep water is estimated as about 1.5m. Such a extremely high surge on coral reef zones can not be supposed from the traditional design concept.

(iii) Bore-like surf beat

Photograph-3 shows a reef coast when the tide is high and at a calm sea condition. In this Photograph, The solid line shows the shore line at high water level condition. And the crown level of the coastal cliff is between 6m and 7m above datum level. The pole held by the man is 2m in height.

Photograph-4 was successively taken with time interval of about 15sec. when a typhoon approached the Okinawan main Island on 9:22 at Aug. 29th in 1987. In photo.(a), the waves superimposed on the surge induced by incoming high wave groups can be seen. When this photo. was taken, the significant wave height at the offshore was about 6m. Photograph-(b) was taken after 15sec from the state in Photo.(a). The white line can seen as the breaking wave near the middle of this Photo. is the front of a surge advancing to the shore. And the short period wave, so-called individual waves, can be seen too. After 15sec from that, the surge attacked the near shore cliff. Photograph(c) shows the attack of the surge.

Photo.-3 Shore line under a calm sea condition (high water level)

(a) 9:22:00

(b) 9:22:15

(c) 9:22:30

Photo.-4 Bore-like surf beat Occurred on Aug. 29, 1987
(Minatogawa coast, T8712)

As seen in photo.-3, the storm surge or surf beat phenomenon on the reef is one of violent wave phenomena. The surf beat very resembles to the Tsunami, so the authors(1988(a) (c), 1990) named it "Bore-like surf beat" or "Tsunami-like surf beat."

Usually, the surf beat has been believed to be a kind of mild and static wave phenomenon compared to the wave with short period. However, as mentioned before, the surf beat phenomenon in the coral reef zone is a violent wave phenomenon. So, we can conclude that they can cause the severe damage on the coastal structures in the reef coasts, where are usually thought that merely the small individual waves exist. And it is clarified that the above mentioned disaster, explained by three engineers, is due to the Bore-like surf beat. Because the interval of the surge attacking the seawall coincided with the natural period of the reef basin.

3. Theory

For the long period fluctuations of mean sea level, the long wave equations has been normally used. Because the violent surf beat phenomenon on the reef is considered, the nonlinear term in the governing equations can not be ignored. Therefore, the Bore-like surf beat, one of the fluctuations of mean sea level, is governed by the long wave equations,

$$\frac{\partial \eta}{\partial t}+\frac{\partial u(h+\eta)}{\partial x}=0 \qquad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+g\frac{\partial \eta}{\partial x}+\frac{1}{\rho(h+\eta)}\frac{\partial Sxx}{\partial x}+\frac{f}{h+\eta}u|u|=0 \qquad (2)$$

where t: time, x: onshore distance from the reef front, η: mean sea-level elevation, u: cross-sectional mean velocity in the vertical section, h: water depth measured from the still water surface, Sxx: x-comporment of radiation stress, ρ: water density, f:bottom friction coefficient, and g: acceleration of gravity. In the momentum equation, a predominant forcing factor of the nonstationary periodic response of water is the term of radiation stress, which is proportional to the square of incident short period wave heights, and varying with time.

The radiation stress at a x from the reef front is given by

$$Sxx=\frac{1}{8}\rho H(x,t)^2\left(\frac{2kh}{\sinh 2kh}+\frac{1}{2}\right) \qquad (3)$$

where H(x, t) is the wave height on x at time t. the time variation of the wave height on the reef can be calculated by

$$\frac{H(x,t)}{H_o(t)} = B\ exp\{-Ax/L\} + \alpha h/H_o(t) \tag{4}$$

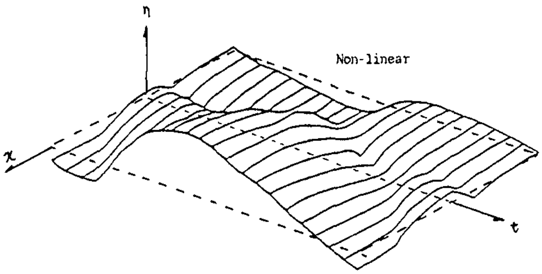
$$H_o(t) = \overline{H_o}(1+0.5 sin\sigma_g t) \tag{5}$$

where Ho(t) : incident wave height at the time t, h: still water depth on the reef, σ_g : angular frequency of incident wave groups. And mean wave set-up on the reef is given by the equation,

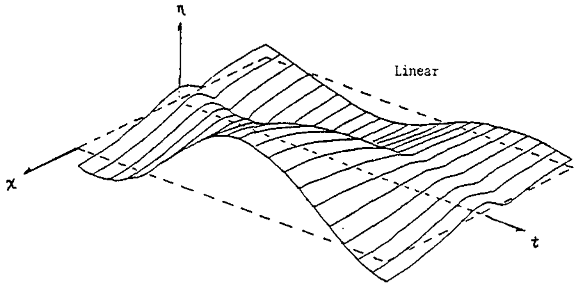
$$\overline{\eta} = \overline{H_o}\left[C - \frac{3}{8}\beta\left(\frac{H(x)}{\overline{H_o}}\right)^2\right]^{1/2} - h \tag{6}$$

The coefficients A, B, C, α and β are proportionality constants to be determined by experiments.

Figure-3 shows the numerical simulation of surf beat taking into account of the non-linear effect of long period fluctuation of mean sea-level, for the wave group period is 27.2sec, and the mean incident wave height $\overline{H}o$=6.5cm. On the other hand, fig.-6 shows the result of simulation by Symonds' Method(1982, 1984) which ignored the non-linear effect. As seen in Fig.-5, compare to the result from liner simulation, the surf



(a) non-linear calculation



(b) linear calculation

Fig.-3 Numerical simulation of Bore-like surf beat

beat profile at shore line very inclines onward. And it shows one of the future of the Bore-like surf beat.

4. Experiment

4.1 Experimental equipments and method

Two-dimensional experiment has been performed using laboratory equipments in Fig.-4. The wave tank is 27m long, 0.7m wide and 1.0m deep. The prototype of reef coast has the reef flat of 400m in width and the steel water depth of 2m. The experiments were conducted with two types of regular and irregular incident wave groups. In this paper, only the results from the case with regular incident wave groups will be explained.

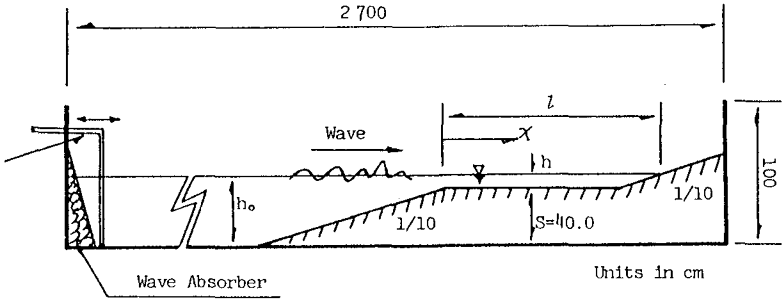


Fig.-4 Experimental equipment

4.2 Results

Figure-5 shows an example of the bore-like surf beat. The upper trace is the profile of deep water waves, and the lower one is the profile of sea surface oscillation on the near shore line. As shown in this figure, the Bore-like surf beat phenomenon is excited by incoming wave groups.

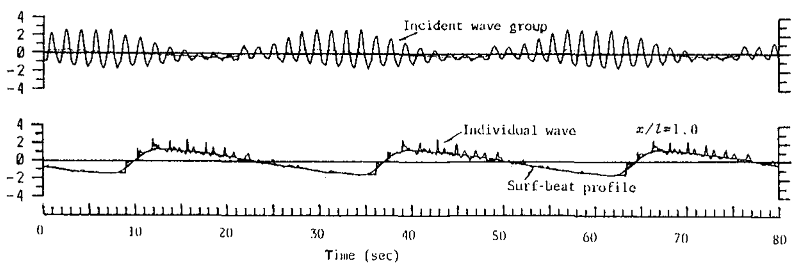


Fig.-5 Example of the experimental waves in deep area and near shore line

Figure-6 shows the comparison of the numerical simulation with the experiments for long period sea oscillation at near shore line. In the figure, circles indicate the experiments, and the solid line represents the results of the numerical simulation. The numerical simulation shows good agreement with the experiments.

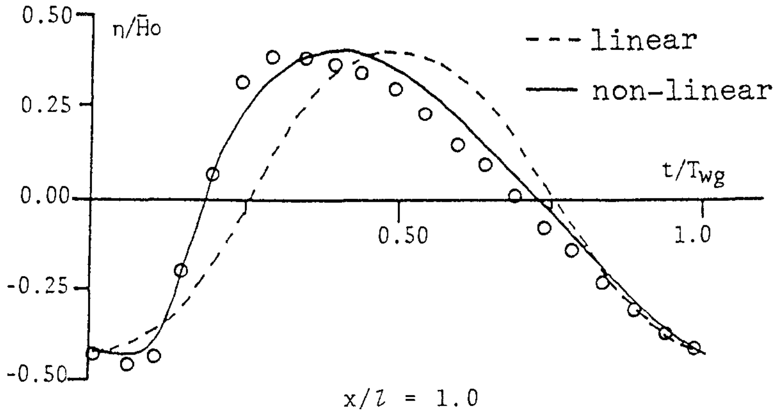


Fig.-6 Comparison of numerical simulation with experiments for long period sea oscillation

Reef coast has the natural period of the seich in a reef basin. Figure-7 shows the oscillation mode of the sea surface in the reef basin. The natural period of the reef coast can be approximately estimated by equation (7).

$$T_o = \frac{4l}{(2n+1)\sqrt{gh}} \quad (n=0,1,2\cdots) \tag{7}$$

where : width of the reef flat, and h: still water level.

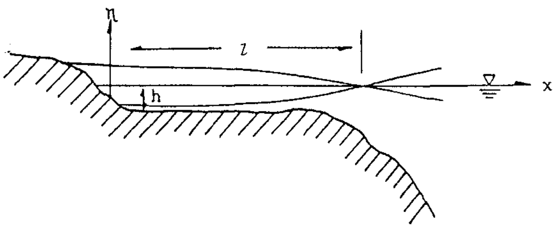


Fig.-7 Long period oscillation mode of sea surface on the reef basin

Figure-8 shows the resonance diagram of sea surface oscillation plotted against the non-dimensional period of wave groupiness. The solid line in the figure corresponds to the numerical solution. As seen in this figure, clear resonant responses are induced when the periods of groupiness of the incoming waves coincide with the natural periods of the reef basin. And the results of numerical solution show good agreement with the experimental results.

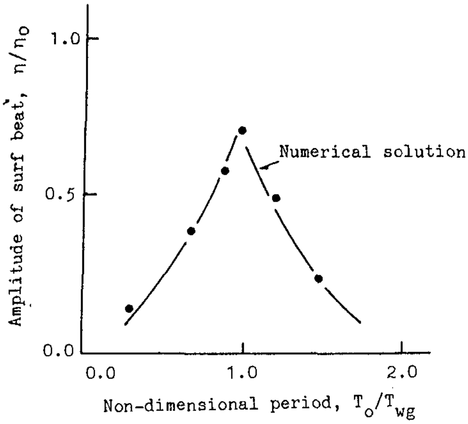


Fig.-8 Resonance diagram
(η_0 , Twg :root mean square amplitude and period of incident wave groups)

5. Field observation of surf beat on the reef

Figure-9 shows records by pressure-type wave gages simultaneously obtained under the Typhoon at three different locations as shown in Fig. 1. The station point 1 is located at 250m offshore from the reef front, the point 2 is located near the reef front and point 3 is located near shore line. As seen in these wave records, wave profile observed at St. 1 shows only the feature of wave groupiness, while the other wave profiles observed at St. 2 and St. 3 show the low frequency oscillation of the mean sea level with period of from 1 to 5 minutes. At St. 3 the high mean sea elevations occurred between 10 and 17 minutes corresponding to the clear incoming wave grouping.

Figure-10 shows the power spectrum of the low frequency oscillation of mean sea level at St. 3. In this Figure, the arrows n1, n2, and n3 indicate the natural frequency of the reef coast for the fundamental mode, second mode, and third mode respectively. The power spectrum has the two peaks corresponding to the natural frequency of the reef coast. Estimating the power spectrum for the lower frequency than the peak frequency nearly corresponding to the significant wave period of the incident waves, we can obtain the frequency response of mean sea level. But straightly calculating from the sea surface oscillation obtained by wave recorder, the low frequency power spectrum of incident waves can not be obtained. In this study, for the slowly varying wave height time history, the smoothed instantaneous wave energy history proposed by Funke-Mansard (1980) is used.

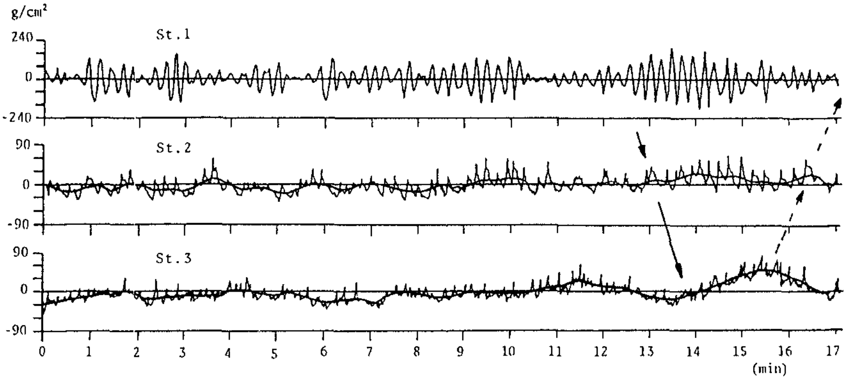


Fig.-9 Wave gage records simultaneously obtained for Typhoon T8520 at three different locations

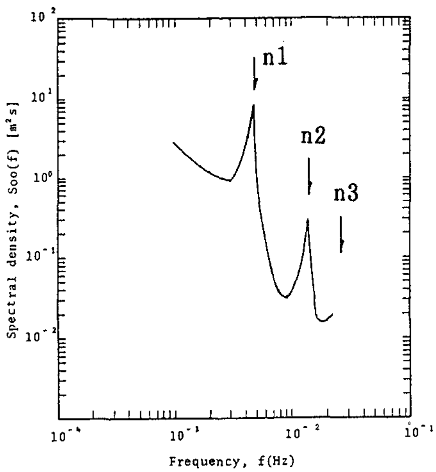


Fig.-10 Power spectrum of the low frequency oscillation of mean sea level at point 3

Figure-11 shows the low frequency power spectrum of incident wave energy. Seeing this figure attentively, it can be noticed that there are two peaks of the low frequency spectrum. The second peak from the lowest frequency is corresponds to the frequency for the repetition length of high waves (Goda's j2). But what does the first peak mean ?. the period for the first peak is about twice of the second peak. The authors has been thought that the surf beat on the reef coasts has resonantly exited by the wave energy on the second peak, because the period corresponds to the natural period of the reef coasts around the Okinawan Islands.

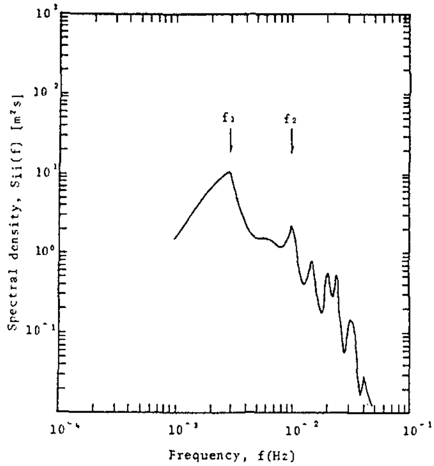


Fig.-11 Low frequency power spectrum of a incident wave groups

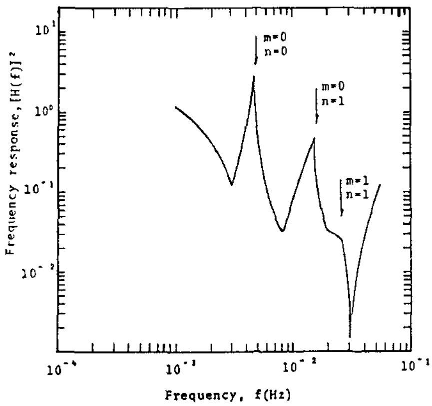


Fig.-12 Frequency response of mean sea level in a reef basin

Considering the linear wave phenomenon, the frequency response of mean sea level with long period is estimated by

$$Soo(f) = |H(f)|^2 Sii(f)$$

Figure-12 shows the frequency response $|H(f)|$. The frequency response has two clear resonant frequency corresponding to estimated ones by equation (2). As seen in this figure, the surf beat (that is to say, Bore-like surf beat) should be considered that it is resonantly exited by incoming wave groups.

6. conclusion

In a coral reef zone, resonant long period oscillations with the predominant natural frequency have been induced by incoming wave groups. The wave groups may resonantly excite Bore-like surf beat on the reef, and the sever disasters of coastal structures on the reef have always been induced by Bore-like surf beat. The simulation taking into account of the non-linear effect of the surf beat is good agreement with experimental one. A method for estimating the low frequency spectrum of incident waves is proposed. The frequency response of mean sea level with long period can be estimated by the method proposed in this study. And it indicates one of the resonant diagram for the long period fluctuation of mean sea level. The frequency response for a reef coast is identified. The periods for the first and/or second peak of the low frequency spectrum can be used in the estimation of occurrence of resonant response of mean sea-level in bays, harbor, and coasts with clear natural frequency.

References

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

Hino, M., et al. (1988a) : A study on a bore-like surf beat induced by wave groupiness, Proc. 35th Japanese Conf. on Cosstsl Eng., pp. 197-201. (in Jspanese)

Nakazs, E. and Hino, M. (1988b) : Coastal disasters due to Bore-like surf beat on reef coasts, Proc. 35th Japanese Conf. on cosstal Eng., pp. 202-206. (in Japanese)

Naksza, E., et al. (1988c) : Wave force due to Tsunami-like surf beat, Proc. 35th Jspanese Conf. on coastal Eng., pp. 597-601. (in Japanese)

Naksza, E. and Hino, M. (1990) : Reef-zone disaster caused by Bore-like surf beat. Coastal Eng. in Jspan.

Seelig, W. (1983) : Laboratory study of reef-lagoon system hydraulics, J. waterway, Port, Coastsl and Ocean Eng., ASCE, Vol. 109, No. 4, pp. 380-391.

Symonds, G. and Bowen (1984) : Interaction of near shore bars with incoming wave groups, J. Geophysical Research, Vol. 89, No. C2, pp. 1953-1959.

Takayama, T., et al. : Wave deformation on the reef coasts, Tech. Rep. of the Port and Hsrbor Res. Inst., No. 278. (in Japanese)

Tsukayama, et al. (1989) : Wave deformation on reef corals, Proc. 36th Japanese conf. on coastal Eng., pp. 70-74. (in Japanese)

Tsukayama, S. et al. (1990) : wave transformation due to the big roughness of coral reef on ses bottom, Proc. 45th Annusl Conf. of the Japan Society of Civil Eng., 2, pp. 756-757. (in Japanese)