Wave Breaking and Wave Setup of Artificial Reef with Inclined Crown

Keisuke Murakami[1] and Daisuke Maki[2]

Beach protection facilities are sometimes required to harmonize with coastal environments and utilizations. This study investigates some hydraulic functions of artificial reef which has an inclined crown. The reef is expected to protect beaches against storm waves, and also facilitates surfing activities under normal wave conditions. This study focuses on wave energy dissipation by the reef, generation of suitable wave breakers for surfing and wave setup behind the reef.

Keywords: artificial reef; wave setup; wave transmission; wave breaker; surfing

INTRODUCTION

An artificial reef is one of the shore protection facilities, and it also has some advantages such as preserving coastal scenery and harmony with fishery resources (e.g. Yano et al. 1997). In addition to these advantages, it has possibility to facilitate surfing activity, and a few types of surfing reefs have already been constructed (e.g. Borrero et al. 1997, Shaw Mead 1997). Surfing reefs have peculiar planar structures. For example, Yoshida et al. (1991) and Nakano et al. (1994) proposed a delta-shaped artificial surfing reef. Furthermore, most of the proposed surfing reefs have an inclined crown, which is one of the common features of surfing reefs, in order to generate suitable breakers for surfing.

Artificial reefs have been constructed for the purpose of shore protection on eroded beaches. Regarding above advantages, it could be a multipurpose shore protection facility if it facilitates surfing activity under normal wave conditions without losing its primal shore protection function under stormy wave conditions.

It is well known that an artificial reef forces wave setup due to excess onshore mass transport over the reef (e.g. JSCE 2000). This phenomenon generates peculiar nearshore circulation around the reef, and this flow sometimes causes offshore littoral drift on the opening between adjacent reefs. The magnitude of wave setup behind the reef relates to the wave dissipation rate and the type of wave breaker on the reef, and those hydraulic characters vary depending on the section of artificial reefs as well as the incident wave conditions. This study investigates some hydraulic functions of artificial reef, which has an inclined crown, with focusing on wave energy dissipation by the reef, generation of suitable wave breakers for surfing and wave setup behind the reef.

EXPERIMENTAL SETUP

The experiments were conducted with using two-dimensional wave tank of 15m in length, 0.6m in height and 0.4m in width. Model scale was assumed 1/30. Fig. 1 shows the section of the models used in this study. The locations of the wave gauges are also shown in this figure. Both Case-A and Case-B has an inclined reef crown of 1/10. The inclined reef crown can be seen as a common section among the surfing reefs to get suitable breakers for surfing. The length of reef is B=0.6m in Case-A and 1.2m in Case-B. Case-C has the same reef length as Case-A, and its reef crown is flat. Case-C was tested in order to compare hydraulic characters with Case-A and Case-B. All models are impermeable.

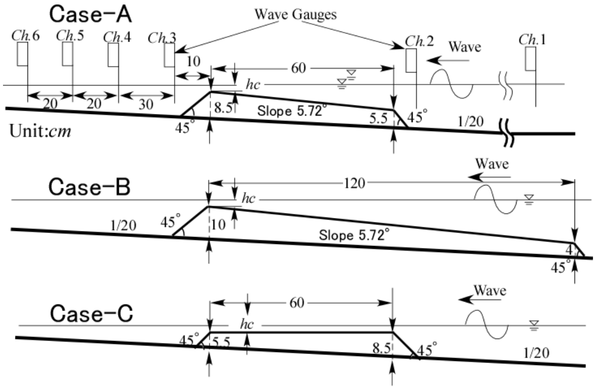


Figure 1. Configuration of artificial reefs tested in experiments

---

[1] Department of Civil and Environmental Engineering, Miyazaki University, 1-1 Gakuen KIbanadai Nishi, Miyazaki, 889-2192, Japan

[2] Faculty of Engineering, Miyazaki University, 1-1 Gakuen KIbanadai Nishi, Miyazaki, 889-2192, Japan

The models were fixed on the impermeable slope of 1/20. The still water depth on the offshore flat section in the tank was maintained as h_0=0.4m. In all cases, water depth at the onshore edge on the crown was hc=0.02m, and this is the minimum water depth on thecrown. The water on the offshore edge of the crown was 0.08m in Case-A and 0.14m in Case-B. Furthermore, the water depth at the offshore foot of the reef was h=0.135m in Case-A, 0.18m in Case-B and 0.105m in Case-C, respectively.

Regular waves were generated in the tank in order to identify breaker type and breaker point clearly. Incident wave period was changed from T=1.0 sec. to 2.4 sec. in 0.2 sec. interval, and incident wave height was also changed from H_0=0.04 m to 0.09 m in 0.01 m interval on each wave period.

Water surface elevation at each location shown in Fig. 1 was recorded in PC with 50Hz sampling frequency. The wave height in front of the reef was measured at *Ch.*2, and transmitted wave was also measured at the locations from *Ch.*3 to *Ch.*6. The wave setup was evaluated by taking moving average of recorded water surface elevation for a series of some waves at transmitted locations during the steady state condition. The width of the moving average coincides with incident wave period on each case.

WAVE SETUP BEHIND THE REEF

It is well known that an artificial reef forces a wave setup due to excess onshore mass transport over the reef. Fig. 2, Fig. 3 and Fig. 4 show characteristics of normalized wave setup, η/H_0, in Case-A, Case-B and Case-C, where H_0 is an incident wave height. Symbols in each figure mean the difference of incident wave height. Wave setups measured at transmitted locations from *Ch.*3 to *Ch.*6 were nearly the same in all cases, and η represents an averaged value of those wave setups.

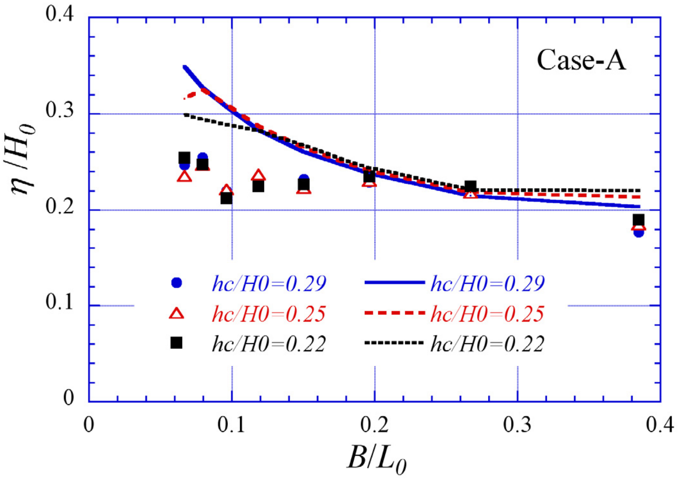


Figure 2. Wave setup behind the artificial reef in Case-A

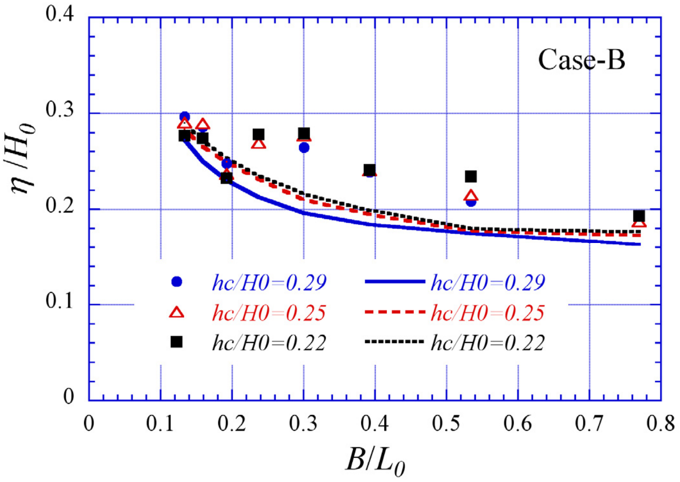


Figure 3. Wave setup behind the artificial reef in Case-B

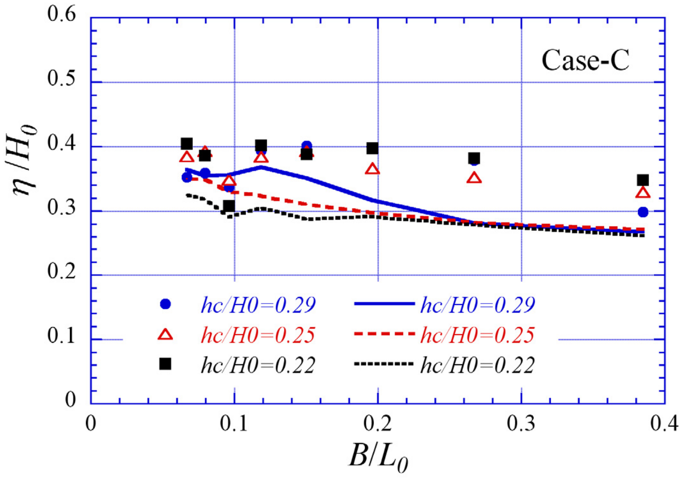


Figure 4. Wave setup behind the artificial reef in Case-C

The lines in each figure are the estimated wave setup calculated from following equation proposed by Takatama et al.(1977).

$$\frac{h_r+\eta_\infty}{H_0} = 0.989\sqrt{\left[\frac{h_r+\eta_0}{H_0}\right]^2+\left[\frac{(H_{1/3})_{x=0}}{H_0}\right]^2} \qquad (1)$$

where h_r means a water depth on the reef. In this study, h_r was defined as an averaged water depth on the inclined reef crown. Both $(H_{1/3})_{x=0}$ and η_0 are the significant wave height and wave setup at the offshore edge of the reef, respectively. Those were estimated from the equations proposed by Goda (1975,2005).

Fig. 2 shows that the artificial reef with inclined crown increases the normalized mean water level, η/H_0, from 18% to 25% in Case-A. η/H_0 tends to decrease with increase of relative reef length, B/L_0, where L_0 means an offshore wave length. The difference of η/H_0 against incident wave height seems very small. As shown in Fig. 3, similar characters can be seen in Case-B, where the mean water level increases from 19% to 29% in this case. On the other hand, as shown in Fig. 4, the mean water level increases from 30% to 40% in Case-C, and the wave setup is larger than Case-A and Case-B. Results shown in Fig. 2, Fig. 3 and Fig. 4 are the cases of larger wave conditions as H_0=7cm, 8cm and 9cm. The characteristics of lower wave setup in Case-A and Case-B were also seen under the cases of smaller wave conditions as H_0=4cm, 5cm and 6cm. Then, wave setup calculated from Eq. 1 showed good agreement in each case, though the equation was derived for the reef with infinity length.

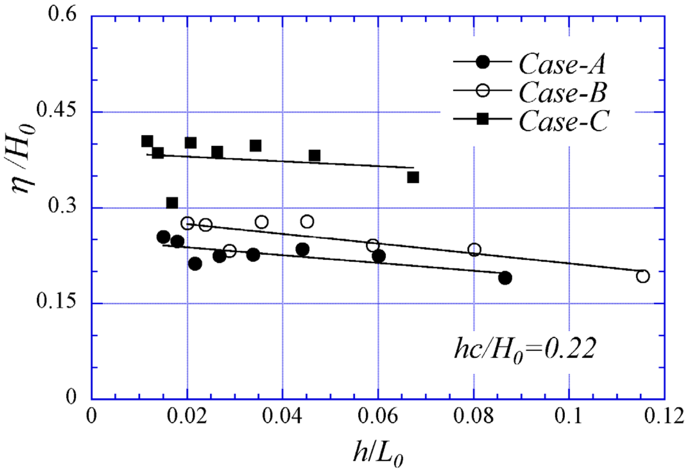


Figure 5. Comparison of the wave setup (hc/H_0=0.22)

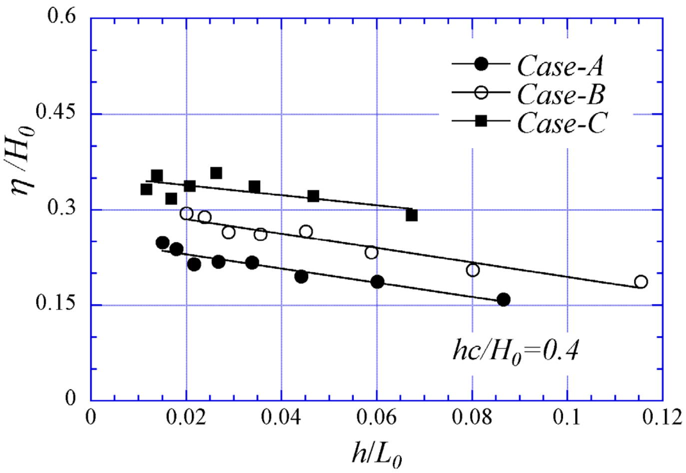


Figure 6. Comparison of the wave setup (*hc*/H_0=0.4)

Fig. 5 shows the comparison of wave setup between Case-A, Case-B and Case-C in the case of larger wave condition as hc/H_0=0.22. Horizontal axes, h/L_0, means a relative water depth at the foot of offshore reef edge. It is apparent that the wave setup in Case-A and Case-B are considerably lower than Case-C. In addition to this, the wave setup in Case-B seems smaller than that in Case-A. Fig. 6 also shows the comparison of wave setup between Case-A, Case-B and Case-C in the case of smaller wave condition as hc/H_0=0.4. In this case, the wave setup in Case-A and Case-B are still lower than Case-C. The deference of wave setup between each reef section comes from the deference of wave dissipation rate, breaker type on the reef and water depth of reef location. In this study, the deference of both wave dissipation rate and breaker type on the reef seems the primal factor of lower wave setup in Case-A and Case-B in comparison with Case-C.

As seen in Fig.5 and Fig.6, the reef with an inclined crown has a function of reducing wave setup on the onshore side of the reef. This advantageous feature comes from the difference of wave deformation which relates to the breaker type on the reef. In Case-A and Case-B, incoming waves amplify on the reef largely and break with plunging type, collapsing type or sometimes intermediate of those types. On the other hand, the incoming waves break on the offshore edge on the reef with backwash type breaker in Case-C. This type of breaker quickly dissipates wave energy at the breaker point with heavy turbulence, and it causes larger wave setup in comparison with Case-A and Case-B.

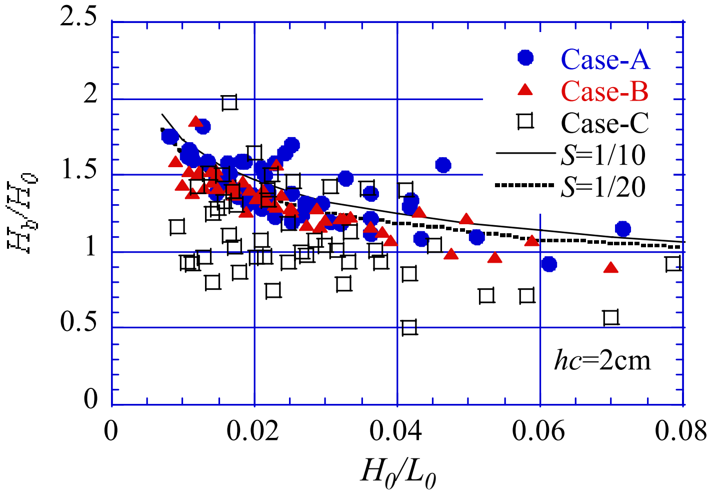


Figure 7. Wave breaker height on the reefs

Fig. 7 shows the normalized breaker height, H_b/H_0, against the incident wave steepness, H_0/L_0. It is clear that Case-A and Case-B amplify incoming waves more effectively than Case-C. This figure also includes estimated breaker height in solid line and dotted line obtained from Goda's breaker index. The breaker height on the inclined reefs is similar to the height estimated on the original bottom slope.

Wave breaker point on the reef in Case-A and Case-B were summarized in Fig. 8. X_b/B means a normalized breaker point, where X_b is the distance measured from the offshore edge of the reef. In Case-A and Case-B, incoming waves break on the reef with plunging, collapsing or intermediate of those types, and their breaker points change depending on the incident wave conditions.

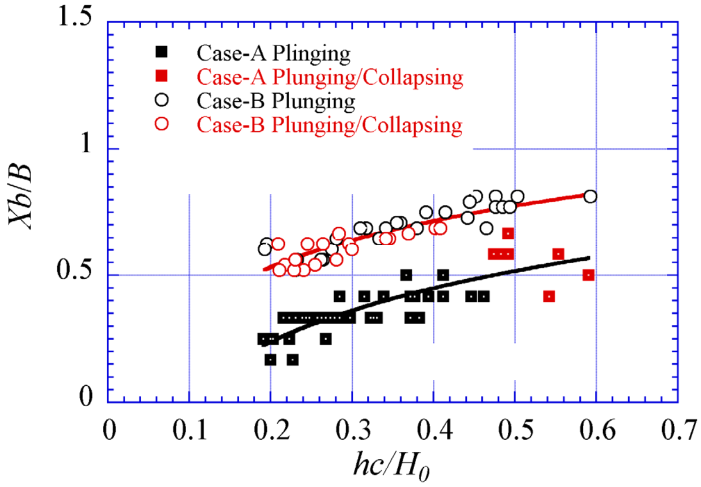
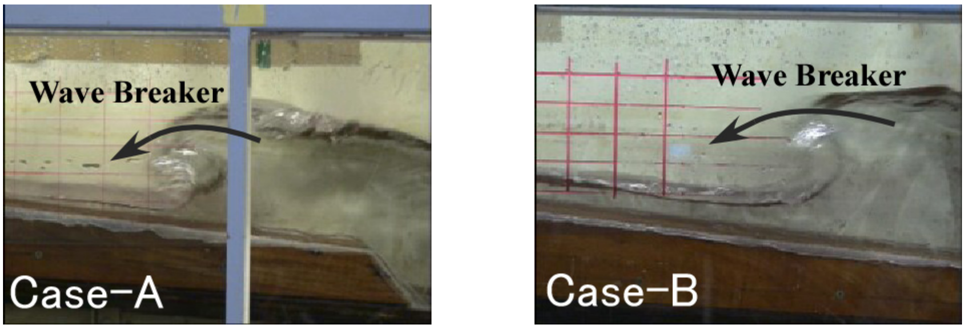
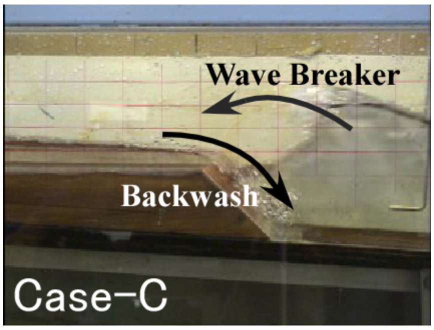


Figure 8. Location of breaker point on the reef crown



(a) Case-A **(b) Case-B**



(c) Case-C

Figure 9. Typical type of wave breaker observed on the reef

As mentioned in Fig.7 and Fig.8, amplified waves break on the reef with plunging type, collapsing type or intermediate of those types. Fig. 9 shows some snapshots of typical wave breakers observed on each reef. As shown in Fig. 9(a) and Fig. 9(b), typical wave breakers observed in Case-A and Case-B were the plunging, collapsing or intermediate of these types. These types of breaker gradually reduce wave energy over the reef. On the other hand, in Case-C as shown in Fig. 9(c), the backwash type breaker was observed at the offshore edge on the reef in most wave conditions. This type of breaker dissipate wave energy largely at the breaker point with heavy turbulent. The difference of these wave deformations cause one of the reasons of lower wave setup behind the reef with inclined crown.

WAVE DISSIPATION FUNCTION OF THE REEF WITH INCLINED CROWN

In the case of constructing an artificial reef near a surf zone, it is difficult to evaluate its wave dissipating function correctly, because transmitted waves sometimes include the complex effects of wave breaking both in front of the reef and on the reef, simultaneously. Takayama et al.(1985) evaluated the wave dissipating function of submerged breakwaters by introducing a coefficient, K_H, which was named influence coefficient and defined as Eq. 2.

$$K_H = \frac{H_{T1}}{H_{T2}} \qquad (2)$$

where H_{T1} is the transmitted wave height behind the submerged breakwater, and H_{T2} is the wave height at the same location in the case of no submerged breakwater on the sea bottom.

This study employs this coefficient in order to evaluate the wave dissipating function of each reef. In this study, H_{T1} is the wave height measured at *Ch*3, and H_{T2} is obtained from the equations proposed by Goda(1975) at the same location of *Ch*3 in the case of no reefs on the sea bottom.

Fig. 10 shows the comparison of influence coefficient between Case-A, Case-B and Case-C in the case of hc/H_0=0.22. Fig. 11 and Fig. 12 also shows the same comparison in the case of hc/H_0=0.29 and hc/H_0=0.4, respectively.

In the case of lager incident wave condition as shown in Fig. 10, incoming waves amplify on the reef largely in Case-A and Case-B, and the intensive forced wave breaking occurs with plunging type, collapsing type or sometimes intermediate of those types. In Case-C, the waves break on the offshore edge on the reef with backwash type breaker as shown in Fig. 9(c). Due to the intensive wave breaking on the reef, the reef with inclined crown has equal wave dissipating function to a flat reef in the case of larger wave condition.

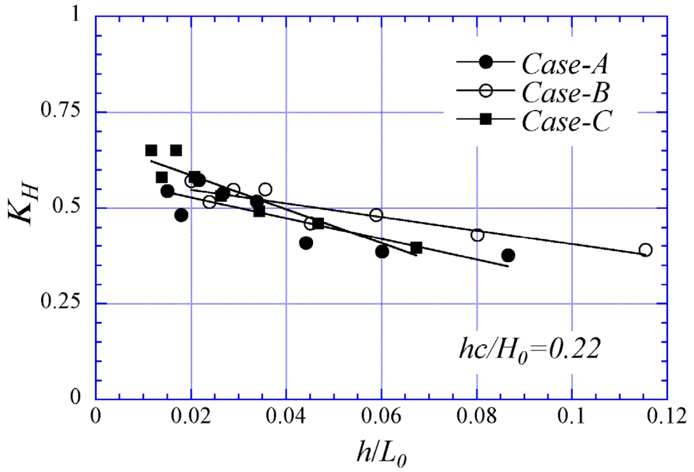


Figure 10. Comparison of influence coefficient (hc/H_0=0.22)

The difference of wave dissipating function can be seen in Fig. 11 and Fig. 12, where the incident wave heights are relatively smaller than those in Fig. 10. The minimum water depth on the reef crown was set as *hc*=0.02m in this study. In Case-C, water depth at the offshore edge on the reef crown was the same as this minimum water depth. On the other hand, the depth at the offshore edge on the crown was 0.08m in Case-A, and 0.14m in Case-B. In the case of relatively smaller incident wave height, the wave energy dissipation by forced wave breaking on the inclined reef crown was insufficient due to the deeper water depth on the offshore reef edge relative to the incident wave height. On the other hand, in Case-C, wave energy dissipation can be expected more than Case-A and Case-B, because shallow water depth on the offshore reef edge forces the backwash type breaker.

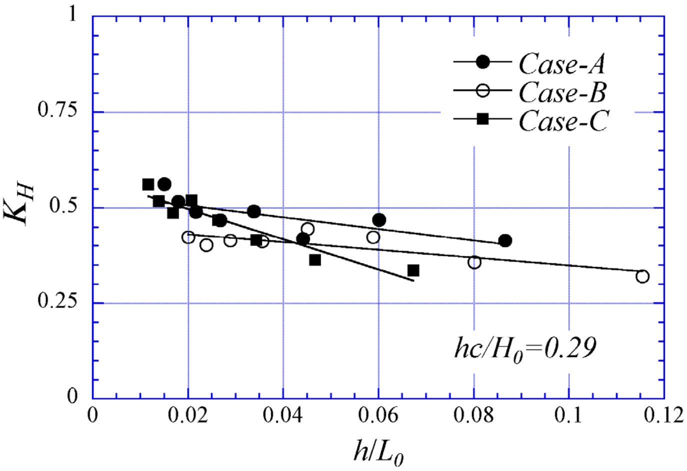


Figure 11. Comparison of influence coefficient (*hc*/*H*$_0$=0.29)

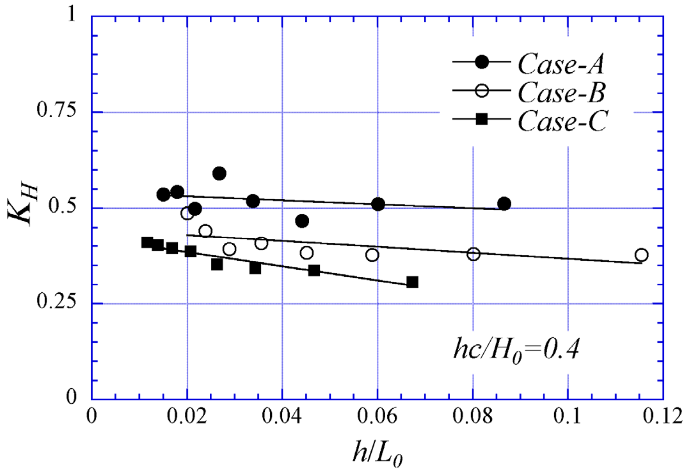


Figure 12. Comparison of influence coefficient (*hc*/*H*$_0$=0.4)

CONCLUSIONS

This study investigated the wave setup behind the artificial reef with inclined crown in order to develop a multipurpose artificial reef that facilitate surfing activity under normal wave conditions without losing its primal shore protection function under stormy wave conditions.

The inclined reef crown plays an important role in generating suitable breakers for surfing in the wide range of incident wave conditions. On the reef with inclined crown in Case-A and Case-B, incoming waves amplify largely and break with plunging type, collapsing type or intermediate of those types in most wave conditions. On the other hand, the waves break on the offshore edge of the reef with backwash type breaker in Case-C with flat crown.

The reef with an inclined crown lowers the wave setup in comparison with the conventional flat crown in the wide range of incident wave height. The plunging type breaker or the collapsing type breaker on the inclined reef gradually reduces wave energy over the reef. On the other hand, the backwash type breaker dissipates wave energy largely on the offshore edge of the reef. The difference of these wave deformations causes one of the reasons of lower wave setup in Case-A and Case-B with inclined crown.

Due to the intensive wave breaking on the reef under the lager wave height conditions, the reef with inclined crown has equal wave dissipating function to the conventional flat crown reef. On smaller wave conditions, wave energy dissipation due to forced wave breaking on the inclined reef crown becomes insufficient because of the deeper water depth on the offshore reef edge relative to the incident wave height.

REFERENCES

Borrero J.C. and C. Nelsen. 2003. Results of comprehensive monitoring program at Pratte's Reef, *Proceeding of 3rd International Surfing Reef Symposium*, 83-98.

Goda Y. 1975. Deformation of irregular waves due to depth controlled wave breaking, *Report of the Port and harbor Research Institute*, Ministry of Transport, Vol. 13, No.3, 59-106.

Goda Y. 2005. Calculation diagrams for wave setup and longshore currents induced by directional spectral waves, *Annual Journal of Civil Engineering in Ocean*, JSCE, Vol. 21, 301-306.

JSCE. 2000. Design manual for coastal facilities, JSCE, 449-455.

Murakami K, D Maki and Y Matoba. 2009. Experimental study on hydraulic characters of artificial reef with inclined crown, *Annual Journal of Coastal Engineering*, JSCE, Vol. 56, 931-935.

Nakano S, T Mishima, K Nakano and H Mitsui. 1994. Characteristics of waves around the delta-shape surfing reef, *Proceeding of Coastal Engineering*, JSCE, Vol.41, 721-725.

Shaw Mead. 2003. Surfing science, *Proceeding of 3rd International Surfing Reef Symposium*, 1-36.

Takayama T, Y Kamiyama and O Kikuchi. 1977. Wave transformation on the reef, *Technical Note of the Port and harbor Research Institute*, Ministry of Transport, No. 278, 301-306.

Takayama T, K Nagai and T Sekiguchi. 1985. Irregular wave experiments on wave dissipation function of submerged breakwater with wide crown, *Proceeding of 32th Japanese Conference on Coastal Engineering*, JSCE, Vol.32, 545-549.

Yano K, A Watanuki, Y Yamamoto, S Aketa and N Hirose. 1997. Hydraulic characteristics and Biota of "High-Crest" submerged breakwater, *Proceeding of Coastal Engineering*, JSCE, Vol.44, 1141-1145.

Yoshida Y,S Nakano, Y Masumi and H Mitsui. 1991. A fundamental study on artificial reefs that serve surf-riding points, *Annual Journal of Civil Engineering in Ocean*, JSCE, Vol. 7, 113-118.