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RESIDUAL CURRENTS PRODUCED BY PLURAL SUBMERGED ASYMMETRICAL STRUCTURES IN WAVE-CURRENT COEXISTING FIELDS

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ABSTRACT

Characteristics of residual currents caused by asymmetrical structures, known as *BaNK* blocks, were experimentally investigated in wave-current coexisting fields. Komatsu *et al*. (2001) proposed the effective method called "Beach and Navigation Keeper: *BaNK* system" in order to cope with beach erosion and shoaling of fairways. The system is a method to control sediment transport using residual currents which are produced by plural submerged asymmetrical small structures in a sea. The system has so far been especially investigated in wave fields by laboratory experiments and numerical simulations. As a result of this study, it is found that an appropriate length of the *BaNK* block unit is about one-fifth of a wavelength in both a wave-only field and a wave-current coexisting field. Furthermore, an estimated optimum on-offshore directional space between the two *BaNK* block units is approximately one-tenth of a wavelength.

Keywords: submerged asymmetrical structure, residual current, wave-current coexisting field and *BaNK* block unit

1. INTRODUCTION

Sandy coasts have been eroding all over the world, and beach erosion has become more severe because of the rise of the sea levels due to global warming. In addition, shoaling of fairways has also become a serious matter of concern. Countermeasures against these problems must be taken as soon as possible.

Komatsu *et al*. (2001) proposed the effective method called *BaNK* System, which can be used to control sediment transport by residual currents produced by plural small submerged asymmetrical structures in wave fields. In this study, we refer to this current as a wave-induced residual current and such structures as *BaNK* blocks. The system is illustrated in Figure 1. Komatsu *et al*. (2001) demonstrated that the *BaNK* blocks set on the bottom of the vertical 2-dimensional wave tank could generate residual currents in the direction of incident waves.

"Adaptive Management" is one of the important characteristics of the *BaNK* system. There are still a considerable number of unclear points concerning the details of sediment transport processes, and as each coastal area has individual characteristics, it is hard to find a perfect solution for sediment transport problems. The *BaNK* blocks are easily installed, added and removed, enabling fine adjustments of layout, spacing and direction to accommodate unexpected reactions. Therefore, this system provides significant flexibility and allows

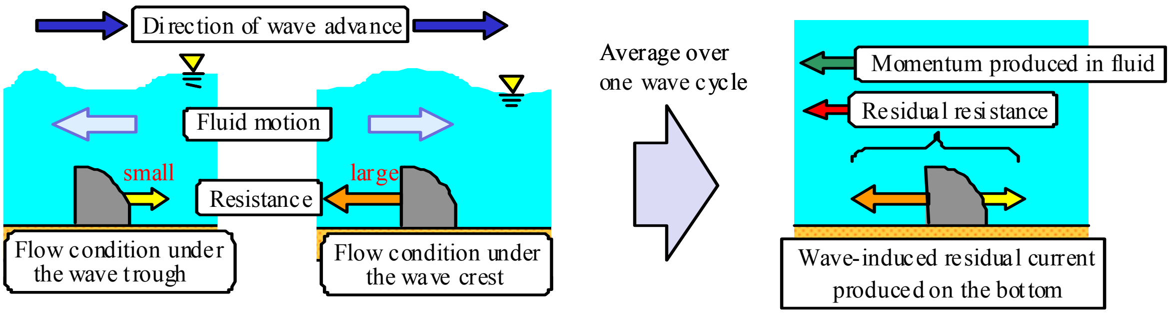

Figure 1 Generation mechanism of wave-induced residual currents in the case with a quarter sphere shaped *BaNK* block.

optimization by observing responses. The findings enable us to understand clearly the unique characteristics of individual coastal area.

The effectiveness of the *BaNK* system in 3-dimensional wave fields was also investigated in the works of Oshikawa *et al*. (2003, 2005). By means of laboratory experiments, the directional characteristics of the residual hydrodynamic force and the wave-induced residual currents produced by *BaNK* blocks were investigated. Furthermore, it became evident that the *BaNK* system could control the littoral drift of sand in a 3-dimensional wave field with a movable bed.

The validity of the *BaNK* system set in the artificial pocket beach was verified at Jigyo Beach in Fukuoka, Japan by Oshikawa and Komatsu (2006). On this beach, seashore transformation is caused by waves. Hence, coastal protection work is needed to restore the damage caused by waves every year. A considerable number of submerged asymmetrical structures were set in the beach for field tests which were performed in 2002 and 2003 with different setting patterns of the structures. The findings of theses tests showed that the *BaNK* system was able to control the beach deformation in the sea.

Oshikawa *et al*. (2006) demonstrated that the *BaNK* system was very effective in countering shoaling of fairways. Fluid mud is one of the main causes of shoaling of fairways. In their study, two kinds of experiments were performed for fine and coarse particles. In the first experiment, fluid mud, which consisted of fine sediments, was substituted by salt water for easiness. The experiment showed a high degree of effectiveness of the system for countering the shoaling of the fairway. The second experiment revealed that the system could control the shoaling of the fairway formed by coarse particles corresponding to sand.

The mechanism of generations of residual hydrodynamic force and residual currents in the *BaNK* system was examined from numerical simulations in oscillatory flows by Oshikawa *et al*. (2007). Simultaneous velocity distributions around an asymmetrical structure were compared with those around a symmetrical one. Furthermore, the residual hydrodynamic force and the residual currents produced by the structure were examined by using the calculated results. From this study, the generation mechanisms of the residual hydrodynamic forces and the residual currents by the asymmetrical structure were made clear.

The aim of the present work is to investigate an appropriate on-offshore length of a *BaNK* block unit and a suitable longitudinal space between the units. *BaNK* blocks would be set up as a unit system in which some asymmetrical structures are put on the surface of a thin slab to form one block unit. This study is based on laboratory experiments measuring velocity distributions around the unit in wave-current coexisting fields.

2. EXPERIMENTAL METHODS

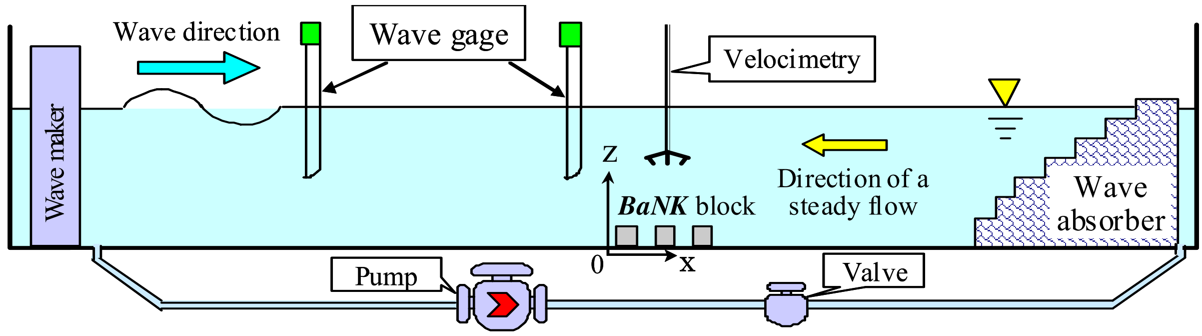

Figure 2 Side view of the experimental set-up.

In a unidirectional wave channel with a pump to generate a steady flow, velocity distributions around *BaNK* block units were measured in detail. The channel is 16m long, 0.25m wide and 0.6m deep shown in Figure 2. Regular waves were generated, at a mean water depth of h=0.3m, and with wave amplitude a=0.025m, period T=1.0s, and wavelength L=1.37m. Two kinds of steady flows were produced by the pump. The cross-sectional averaged velocity, V, was 1 or 2 cm/s. The test under the only wave existing condition was also carried out without the use of the pump. The direction of the steady flows was opposite to residual currents made by the asymmetrical structures near the bottom. The steady flows were applied instead of tidal currents whose periods are much longer than those of waves. In other words, we focus on whether steady flows cancel residual currents produced by the asymmetrical structures.

In this study, half cylinders were used as the asymmetrical structures of the *BaNK* block. Half cylinders, in which the diameter D and the height k were 3.0cm and 1.5cm respectively, were used as protuberances on the *BaNK* block unit (see Figure 3). Protuberances were positioned in a grid pattern with 6.0cm intervals for all cases (see Figure 4). These half cylinders were set so that wave-induced residual currents would be produced near the bottom in the direction of the wave absorber from the wave maker (see Figures 2 and 4).

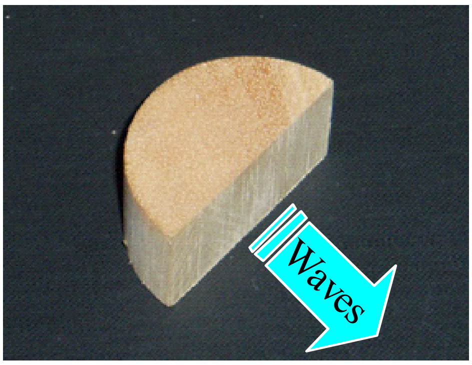

Figure 3 A half cylinder used as a protuberance to form a *BaNK* block unit.

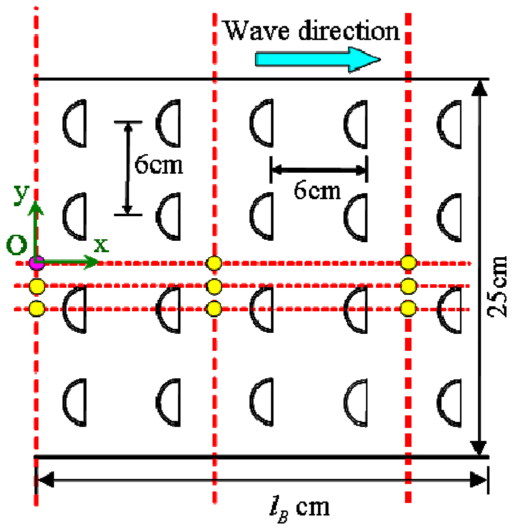

Figure 4 Top view of the *BaNK* block unit and horizontal measured points of the vertical velocity distributions in the case of CaseA-3. The small circles denote the points.

Three components of velocity were measured by an acoustic Doppler velocimetry (Nortek AS, Vectrino). A coordinate system was illustrated in Figures 2 and 4. The velocity data obtained for 100 wave cycles were digitalized at a sampling frequency of 50Hz. In this study, wave-induced residual currents defined as Eulerian velocity averaged over the wave period are used to estimate an optimum length of the unit.

Two kinds of experiments were performed in this study. Firstly, in the uniform space for each asymmetrical structure, the longitudinal number of protuberances per one unit was varied in order to examine a suitable length of a *BaNK* block unit. This series are called as Experiment-A. Secondly, two *BaNK* block units whose size was decided in the Experiment-A were set in various spaces to estimate the reasonable on-offshore space between the units. The latter series are called as Experiment-B.

Methodology on Experiment-A

The purpose of Experiment-A was to investigate an appropriate on-offshore length of a group of asymmetrical structures. In the Experiment-A, the number of protuberances set in the on-offshore direction is varied for each case (see Table 1), where l_B denotes the length at which structures are placed. On the other hand, the number of protuberances in the transverse direction is constant 4. In these cases, velocity distributions were measured both in the wave-current coexisting fields and in the wave only field. However, in CaseA-2 and CaseA-4, measurements were performed in the wave only field.

Table 1 The longitudinal number of protuberances per one *BaNK* block unit and the corresponding lengths in the Experiment-A.

	CaseA-1	CaseA-2	CaseA-3	CaseA-4	CaseA-5	CaseA-6
The number of blocks	3	4	5	7	11	15
l_B (cm)	18.0	24.0	30.0	42.0	66.0	90.0
l_B / L	0.131	0.175	0.219	0.306	0.481	0.656

Measured points in the x-direction were different in each case. The number of vertically measured sections in the x-direction was 3 in CaseA-3 and CaseA-4: the sections were near the both edges of block set areas in each case and at the middle of them (see Figure 4). That was 6 in CaseA-5 and 8 in CaseA-6 in a uniform interval encompassing the corresponding 3 sections. However, in CaseA-1 and CaseA-2, the measurements were performed only near the both edges because the longitudinal lengths were too short to measure at the 3 sections. In the y-direction, velocity distributions were measured at the three sections (y=0, -1.5, -3.0cm) in each case. Those were vertically done at z = 0.1, 0.375, 0.75, 1.5, 2.25, 3.0, 4.0, 5.0, 7.0, 10.0, 15.0 and 20.0cm in all cases.

Methodology on Experiment-B

In order to examine the effects of the space between two *BaNK* block units decided in the Experiment-A on residual currents, three lengths of the space are tested (see Table 2), where l_s denotes the width of opening between two units. The each unit corresponds to the unit of CaseA-3 (see Figure 4). In each case, velocity distributions were measured in the same three flow conditions as the Experiment-A: the two kinds of wave-current coexisting fields and the wave-only field. Measured vertical sections and transverse ones agree with those in the Experiment-A. On the other hand, longitudinal ones are three: at centres in each unit and middle of the two units.

Table 2 The on-offshore spaces between the two *BaNK* block units in the Experiment-B.

	CaseB-1	CaseB-2	CaseB-3
l_s (cm)	11.0	28.0	45.0
l_s / L	0.0803	0.204	0.328

3. RESULTS AND DISCUSSIONS

Sediment transport can be controlled by the *BaNK* system because residual bottom currents are induced around a *BaNK* block unit. In this study, only residual currents are treated and sediment transport is not done, however residual currents should take charge of substance transport and control sediment transport as demonstrated by Komatsu *et al*. (2001), Oshikawa *et al*. (2005, 2006) and, Oshikawa and Komatsu (2006).

Unit length of *BaNK* block (Experiment-A)

Residual currents are produced even when an opposite directional steady flow is added. As examples of the results, vertical 2-dimensional distributions of residual currents at y=-3.0cm are shown in Figure 5 for the wave-only field and in Figure 6 for the wave-current coexisting field of V=1cm/s. The both figures have 3 cases: a) CaseA-1, b) CaseA-3 and c) CaseA-5. A square in the figures denotes a position and a magnitude of the structures.

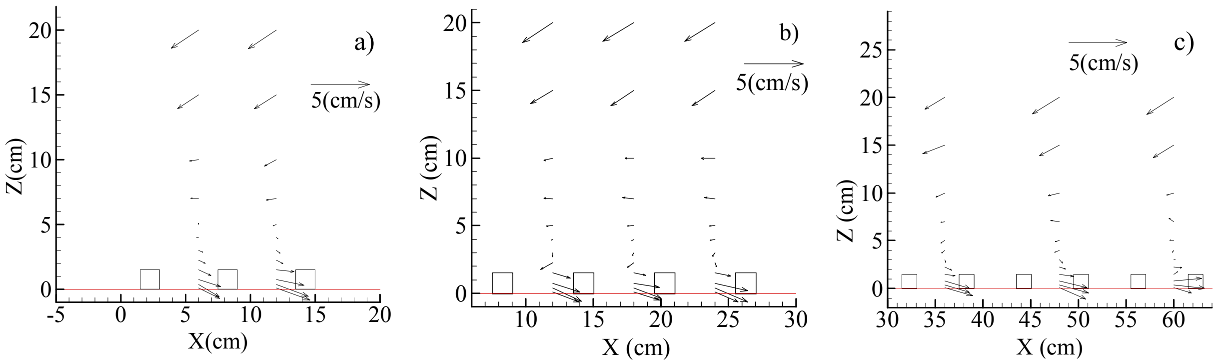

Figure 5 Vertical 2-Dimensional residual current distributions in three cases with the only waves: a) CaseA-1; b) CaseA-3; c) CaseA-5.

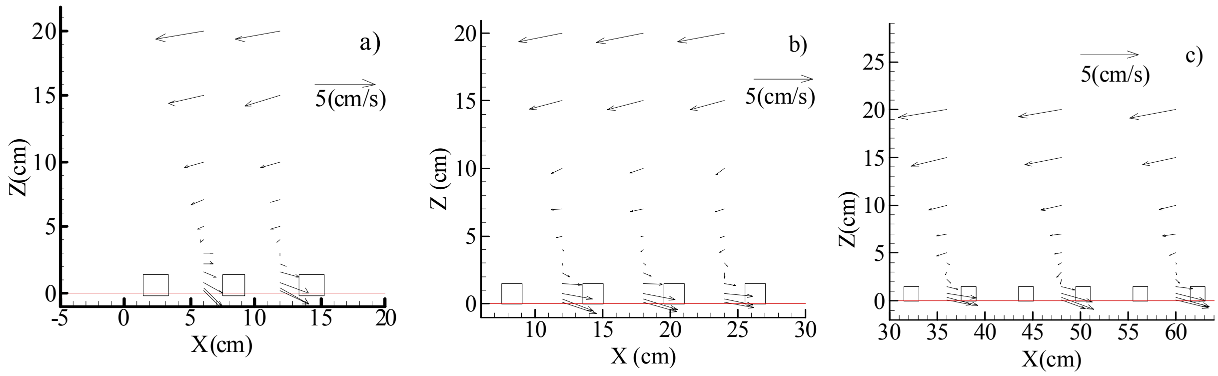

Figure 6 Vertical 2-Dimensional residual current distributions in three cases with the waves and 1cm/s steady flows: a) CaseA-1; b) CaseA-3; c) CaseA-5.

In the cases of wave-only field, from Figure 5, onshore residual currents are produced near the bottom regions due to the asymmetrical structures. On the other hand, compensated offshore residual currents for the onshore ones are found in the middle and the upper regions. These flow structures correspond to the wave-induced vertical circulating currents in the work of Komatsu *et al*. (2001). The same flow pattern appeared in all cases of wave-only field.

The residual flow structures in the wave-current coexisting field are analogous to those in the wave-only field. In Figure 6, onshore residual currents are found near bottom regions even when the opposite directional steady flows are added to the residual currents generated only by waves. Main differences between Figure 5 and Figure 6 are observed in the middle and the upper regions as the absolute values of the residual currents in Figure 6 are larger than those in Figure 5 at $z \geq 7.0$cm due to the steady flow. In addition, flow structures are independent of lengths of the block unit compared among the cases of different lengths in both Figures 5 and 6.

The appropriate length of the *BaNK* block unit was almost one-fifth of the wavelength both in the wave-only field and in the wave-current coexisting fields. The relationship between the representative residual current on the block, U_m, and the unit length l_B are shown in Figure 7. The U_m, which is a locally averaged on-offshore residual current as a representative velocity around the unit, is transversely averaged over all measured points and vertically averaged up to the height of the structures from the bottom. The ordinate is normalized by $a\sigma$, where σ denotes the angular frequency being $2\pi/T$ and π is the circular constant. The abscissa is normalized by L. There are the peaks at l_B/L=0.219 having nothing to do with the steady currents. Generally speaking, x-directional simultaneous velocity under waves has both positive and negative values in one wavelength. Therefore, on a *BaNK* block unit, one directional flow coexists with the opposite directional flow in cases of a long unit length, so that unidirectional residual currents are restrained. Hence, the *BaNK* block unit whose length is almost correspondent to one-fifth of a representative wavelength should produce maximum residual currents.

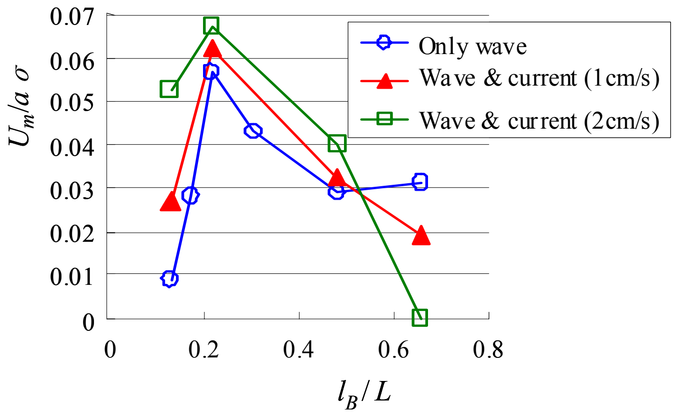

Figure 7 Relationships between the dimensionless on-offshore lengths of the *BaNK* block unit and residual currents on the center of the unit.

In Figure 7, the residual current near the bottom region becomes greater as the opposite directional steady flow increases. Moreover, in all cases, expected positive residual currents are produced. Therefore, the *BaNK* system would be useful even in a tidal current field with waves.

Interval of two *BaNK* block units (Experiment-B)

Residual currents are also produced at a vacant space between *BaNK* block units even though the space is considerable large. Figures 8, 9 and 10 present vertical 2-dimensional residual current distributions at y=-3.0cm. In each figure, "a)" is a case of the wave-only field and "b)" is a case of the wave-current coexisting field (V=1cm/s). In the figures, flow patterns are almost same: onshore residual currents are generated up to 2-3 times of the height of the structures, and offshore ones are done at the middle and the upper regions. In only the case of l_s/L=0.328 with the steady flow, the bottom residual currents between the two units are small because the space is pretty large. However, the currents are large enough in the case of l_s/L=0.328 without the steady flow.

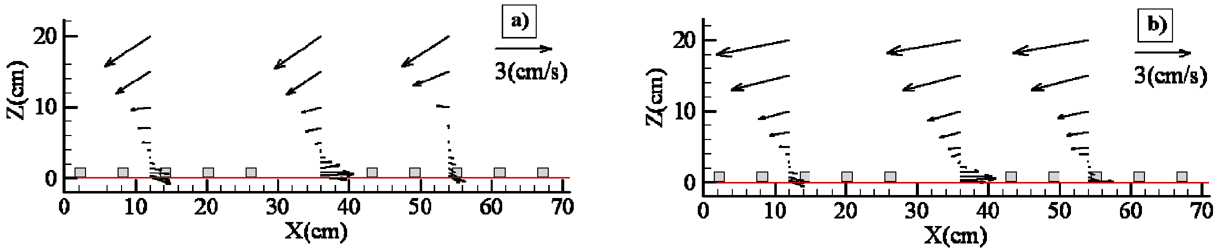

Figure 8 Vertical 2-Dimensional residual current distributions in CaseB-1. a) the only waves, b) the waves and 1cm/s steady flows.

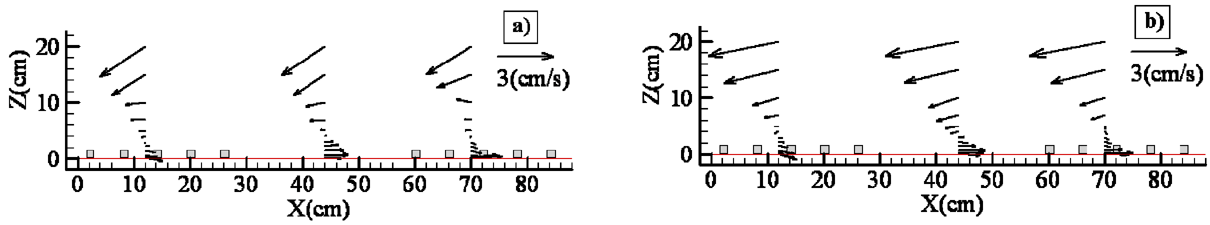

Figure 9 Vertical 2-Dimensional residual current distributions in CaseB-2. a) the only waves, b) the waves and 1cm/s steady flows.

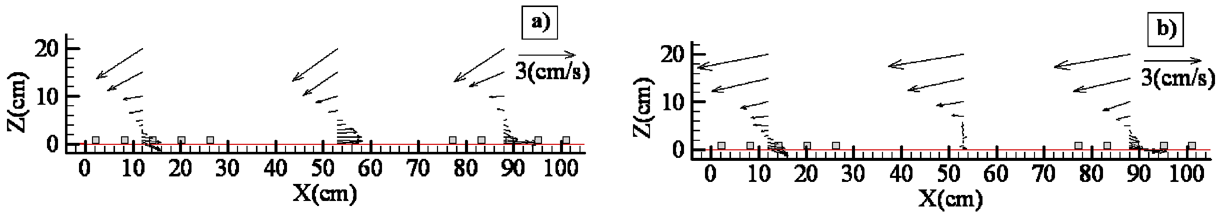

Figure 10 Vertical 2-Dimensional residual current distributions in CaseB-3. a) the only waves, b) the waves and 1cm/s steady flows.

The optimum on-offshore space between the two *BaNK* block units is found to be approximately one-tenth of the wavelength both in the wave-only field and in the wave-current coexisting fields. The relationship between representative residual currents at the middle of the two units, U_m^*, and the length of the space between them, l_s, are illustrated in Figure 11. U_m^* is an on-offshore residual current averaged in the same manner as U_m. The ordinate and the abscissa are normalized by U_m and L, respectively. U_m^* at l_s/L=0 is based on the corresponding result in CaseA-5 where a longitudinal unit length is equivalent to almost double length of the unit in the Experiment-B. The peaks at l_s/L=0.0803 in all cases with the steady currents and without ones are found. Hence, maximum residual currents are generated by the *BaNK* block units which are set at intervals of approximately one-tenth of a representative wavelength.

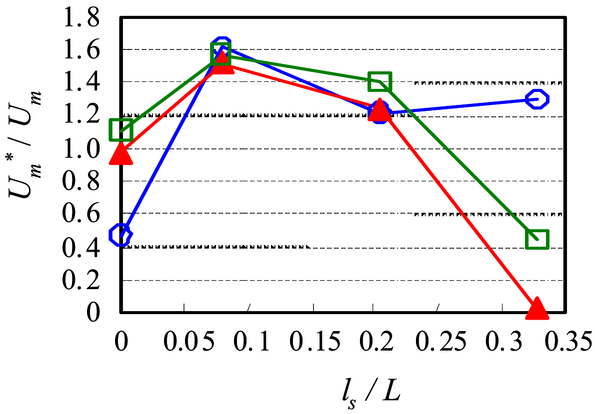

Figure 11 Relationships between the dimensionless on-offshore lengths of the space between two *BaNK* block units and residual currents at the middle of the two units. The legend is the same as Figure 7.

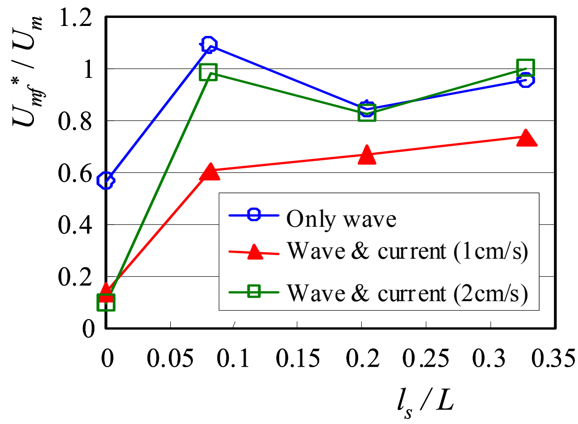

Figure 12 Relationships between the dimensionless on-offshore lengths of the space between the two units and residual currents on the center of the first unit.

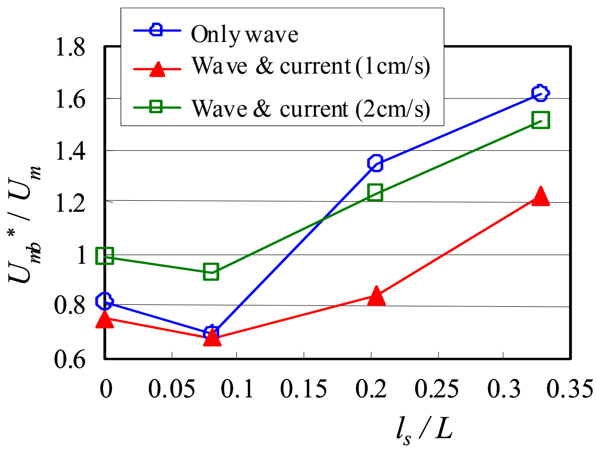

Figure 13 Relationships between the dimensionless on-offshore lengths of the space between the two units and residual currents on the center of the second unit.

The reasonable length of the space between the two block units could be extended to about one-third of the wavelength. It is preferable that a space among block units is longer because the number of units used can decrease practically. In Figure 11, the residual currents are positive in all conditions although there was no block around the measured points. However, it should be difficult to extend the dimensionless length more than 1/3 since U_m^* at l_s/L=0.328 (≅1/3) is little in the cases with the steady flows [see Figure 10b)].

Residual currents on a first unit are almost independent of the space between the two units. The first unit corresponds to the unit set at the offshore side in this study. The relationship between the representative residual currents on the first unit, U_{mf}^*, and l_s are presented in Figure 12. The U_{mf}^* averaged in the same manner as U_m is the locally averaged longitudinal residual current on the first unit. The ordinate and the abscissa are normalized by U_m and L, respectively. For U_{mf}^* at l_s=0, the results in CaseA-5 are used. From Figure 12, we can see that U_{mf}^* is almost same as U_m in the range of $0.0803 \leq l_s/L \leq 0.328$. On the other hand, U_{mf}^* becomes small as l_s/L is too small like the cases where l_s/L=0; the two units are equivalent to a long unit when the space is too small (see Figure 11).

The space between the *BaNK* block units should be extended up to approximately one-third of the wavelength. Figure 13 is a display of the relationship between the representative residual currents on the second unit, U_{mb}^*, and l_s. The second unit is the one set at the onshore side in this study. The U_{mb}^* is the locally averaged on-offshore residual current on the second unit which is averaged in the same manner as U_m. The figure is normalized like Figure 12. The results in CaseA-5 are also used for the U_{mb}^* where l_s/L=0. The residual currents on the second unit become greater as l_s/L increases in the range of $0.0803 \leq l_s/L \leq 0.328$, and are almost constant where $l_s/L \leq 0.0803$. The second unit is influenced by the first one in cases where the unit space is not so long; the experiment by Komatsu *et al*. (2001) revealed that residual currents expand over the block set area, especially in the progressing direction of bottom residual currents. The U_{mb}^*/U_m may approach unity in a range where l_s/L becomes large because there should be no interaction between the two units having enough long space. It may be more economical to extend the space to l_s/L=0.328≅1/3 from 1/10 corresponding to the maximum of U_m^*: to reinforce residual currents on following units.

4. CONCLUSIONS

The objective of this study was to examine the effective unit size of *BaNK* blocks and the spaces between the units. A *BaNK* block unit is formed by plural asymmetrical structures. Various on-offshore lengths of a unit were tested in wave-current coexisting fields. In addition, intervals of optimum two units were also investigated in the fields.

The residual current on the unit is largest whose length is approximately one-fifth of the wavelength having nothing to do with the interrupting steady flows. Therefore, each *BaNK* block unit should be formed in the length of about one-fifth of a dominant wavelength in a sea. We can form the required length unit for the dominant wavelength by setting continuously common, relatively short block units practically.

The residual currents between the two block units have maximum values in the length of approximately one-tenth of the wavelength, which is independent of the steady flows. However, the residual currents on the second block unit become greater as the spaces increase up to at least 1/3 of the wavelength. Economically, we want to extend unit spaces as long as possible. Hence, the optimum condition of each unit space under a dominant wavelength would be in the range 1/10 to 1/3 since residual currents might have negative directions in the rate of more than 1/3. We have to confirm these findings under conditions where three or more *BaNK* block units are placed.

Sediment transport is thought to be controlled by the *BaNK* system because residual currents resulting from asymmetrical structures are produced in a quite large area in wave-current coexisting fields. Residual currents are closely associated with substance transport. Therefore, effective control of substance transport by using the *BaNK* blocks can be expected.

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