EVOLUTION OF NEARSHORE CURRENTS AROUND SUBMERGED BREAKWATERS

Roshan Suminda Ranasinghe[1], Made Jaya Muliawan[2]

Submerged breakwaters are becoming increasingly popular as they offer number of aesthetic and environmental advantages over the other shore protection structures. However the utilization of submerged breakwaters for shore protection is relatively new hence proper design guidelines are yet to be established. Though there are a few studies on submerged breakwaters on laboratory scale and prototype scale at present, most of them focus on wave transformation and very little is known about the evolution of nearshore currents in the vicinity of these structures, which is important for predicting morphological changes around them. The goal of this study is to analyze the patterns of nearshore circulation currents behind the submerged breakwater system hence investigate the influential parameters, which lead these circulation currents. The results obtained from present study are found to be helpful in understanding complex nature of nearshore currents around submerged breakwaters and investigating predictive skills of numerical models.

INTRODUCTION

Submerged breakwaters have become popular for shore protection, and have drawn worldwide attention over the last few decades mainly because of their aesthetic advantage. At the same time these structures only provide partial barrier to the sediment fluxes, which means designers have more control in designing a desired coastal response. On the other hand, water exchange around submerged breakwaters is considered to be better than that of their emergent counterpart; therefore it is advantageous for surrounding marine environments.

As submerged structures are relatively new for shore protection, presently very little is known about the hydrodynamics and the resulting beach morphology in the vicinity of these structures. Obviously there exists a lack of literature on the evolution of nearshore currents around submerged breakwaters. Some exceptions are Shimozono et al. (2005) who presented spatial mean current distributions around submerged breakwater systems under normal incident waves using PTV (particle tracking velocimetry) technique and Ranasinghe and Sato (2007) who explained complex current patterns behind single submerged breakwater under obliquely incident waves on both fixed and movable beds. Due to this lack of knowledge on functional design parameters, some of the submerged breakwaters constructed so far have resulted in failures (e.g. Deguchi and Sawaragi, 1986, Douglass and Weggel, 1987, Dean et al., 1997). This insecurity is again forcing local authorities to go for the well-known emergent type of breakwaters for beach erosion mitigation, which is sacrificing potential advantages offered by submerged breakwaters.

The primary objective of this particular study is to investigate the physical mechanisms of evolution of wave-induced currents around submerged breakwaters. Assuming that a large current circulation

[1] Department of Civil Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan. sumrosh77@yahoo.com
[2] ConocoPhilips Indonesia inc. Ltd., Ratu Prabu 2 building TB. Simatupang Kav 18, Jakarta Selatan, Indonesia.

converging behind the structure would enhance the sediment entrapment; scales of these circulations are analyzed to investigate influential parameters (length of the structure, offshore distance, freeboards, gap width, no. of breakwaters etc.), which lead these circulation currents. Secondly, the physical model results obtained are used to validate the present numerical model, in which the energy dissipation due to wave breaking is modeled by an eddy viscosity type of formulation.

LABORATORY EXPERIMENTS

Experiment set-up

Experiments were performed for three submerged breakwater system and infinite number of breakwater system in a wave basin with dimensions 11mx6.5mx0.3m using normal incident monochromatic waves. This wave basin was equipped with wave paddles capable of creating multi-directional random waves. The system could be run with the "reflection absorption mode" that was designed to eliminate any reflection from the wave generating boards. The average distance from the wave generating boards to the submerged breakwaters was around 4.25m (the distance to shoreline from structures varied between 80cm-120cm), which was approximately 2.3-3.0 times the local linear wavelength on average.

Wave environment was kept the same for all the experiments, which were performed, to bring down the number of parameters associated and only the structural dimensions were varied except the crown width (all the model breakwaters were concrete blocks of fixed size). For three submerged breakwater system, the gap width was varied from 5cm in 5cm intervals and for infinite number of breakwater system it was varied from 10cm in 10cm intervals. Table 1 shows the other structural dimensions associated with each setup, where *3B* stands for three submerged breakwaters and *IB* stands for infinite number of breakwaters.

Table 1. Structural dimensions associated with the laboratory experiments.

Freeboard *Fb* (cm)	*Xs* = 80cm			*Xs* = 100cm			*Xs* = 120cm		
	Ls (cm)								
	56	84	112	56	84	112	56	84	112
0	3B1 IB1	3B1 IB1	3B1 IB1	IB4	IB5	IB6			
1				3B7 IB7	3B8 IB8	3B9 IB9			
2							3B10 IB10	3B11 IB11	3B12 IB12

Particle tracking velocimetry (PTV) technique

Particle Tracking Velocimetry (PTV) offered a flexible technique for the determination of the velocity field associated with wave action. It was based on the visualization of a flow with small neutrally buoyant particles and their image sequences. A video clip recorded by a camera mounted vertically above the flow field was processed and analyzed sequentially in order to determine the current field.

It was essential to use small neutrally buoyant particles as tracers to minimize the difference between the fluid and the particles. The tracer particles were red colored plastic balls of 6mm in diameter and a specific gravity of 1.05, which were found to be the best choice as they could be clearly detected on a white background. The speed of a particle was tracked using two successive images. The identity of each particle was assumed to be the closest particle in the successive image. By tracking the particles in successive images their trajectories could be derived over a number of wave cycles. The velocity vectors were then determined, by dividing the displacement vectors by the time step between two successive images. Since the particles were not uniformly distributed within the domain of the experiment, in certain areas the velocity vectors were interpolated from the surroundings. Finally, the current field was calculated by taking temporal average of the velocity vectors over a number of wave cycles.

NUMERICAL EXPERIMENTS

As far as numerical modeling of waves and currents around submerged breakwaters is concerned there are many complex characteristics to be dealt with. Waves may have strong non-linearity especially around the structure. Shoreward volume flux over the submerged breakwater may cause strong return flow sides of the structure. This strong off-shoreward current may even significantly change the dispersion properties of surrounding waves. Certain fractions of waves may be reflected at the structure and interact with incident waves creating partial standing waves. Apart from those, under small freeboards submerged breakwaters may be subjected to wetting and drying coexisting field, which makes numerical modeling more and more complex. A proper numerical model must then be able to simulate all these characteristics both qualitatively and quantitatively.

Model equations

To account for those complex hydrodynamic characteristics mentioned above, a time-dependent, non-linear, dispersive wave model is the most straightforward approach hence the present model is based on Boussinesq-type equations derived by Nwogu (1993), but with slight modification to the continuity equation. This modification has been preferred on physical grounds, as mass flux should go to zero, when total water depths are zero. This condition is not automatically satisfied by original Nwogu (1993) model equations, making application of the original model problematic at the shoreline. On the other hand it was necessary to make such modification to employ slot technique proposed by Madsen et al. (1997) for simulating the moving shoreline.

Mass conservation equation;

$$\gamma(\eta)\eta_t + \nabla.M = 0 \qquad (1)$$

where, $$M = A(\eta)\left[u_\alpha + \left(\frac{z_\alpha^2}{2} - \frac{h^2}{6}\right)\nabla(\nabla.u_\alpha) + \left(z_\alpha + \frac{h}{2}\right)\nabla[\nabla.(hu_\alpha)]\right] \qquad (2)$$

$\gamma(\eta)$, $A(\eta)$ represent width and cross-sectional area of the numerical wave flume respectively.

Momentum conservation equation;

$$u_{\alpha t} + (u_\alpha.\nabla)u_\alpha + g\nabla\eta + \frac{z_\alpha^2}{2}\nabla(\nabla.u_{\alpha t}) + z_\alpha\nabla(\nabla.(hu_{\alpha t})) + F_f - R_b = 0 \qquad (3)$$

Two additional terms have been introduced into momentum conservation equation to simulate the energy dissipation of wave energy due to bottom friction and wave breaking, which are represented by F_f and R_b. Following Kennedy et al. (2000), a simple eddy viscosity type of formulation is used to simulate energy dissipation due to breaking and the rate of wave energy dissipation is expected to be governed by the magnitude of the eddy viscosity, which is related to the turbulent kinetic energy, k, and a turbulent length scale, l_t. The turbulent kinetic energy is determined from a semi-empirical transport equation with a source term for turbulent kinetic energy production by wave breaking (Nwogu and Demirbilek, 2001);

$$k_t + u_s.\nabla k = \sigma\nabla.\nabla(\nu_t k) + B\frac{l_t^2}{\sqrt{C_D}}\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right]_{z=\eta}^{3/2} - C_D\frac{k^{3/2}}{l_t} \qquad (4)$$

To overcome any instability when the submerged breakwaters are under wetting and drying coexisting field, we follow similar procedure to Madsen et al. (1997) slot technique. Considering the submerged breakwaters are structures with finite porosity, the model does not need any special treatments at the boundary of the wet and dry area.

RESULTS & DISCUSSION

As it was mentioned previously, main set of experiments was performed keeping the wave environment the same but it was necessary to select an appropriate one to proceed. In that regard, six preliminary experiments were conducted keeping structural dimensions $Ls = 84$ cm, $Xs = 100$ cm, $G = 30$ cm, $F_b = 1$ cm (refer to Fig. 1 (b), infinite number of breakwaters) the same but changing wave heights and wave periods. Different wave environments used in the preliminary set of experiments are listed in Table 2.

Table 2. Wave conditions used in preliminary experiments.

	Case01	*Case02*	Case03	Case04	Case05	Case06
Deepwater wave height (m)	0.037	0.037	0.037	0.032	0.032	0.032
Wave period (s)	1.6	1.25	1.0	1.6	1.25	1.0

Spatial distributions of nearbottom current velocities associated with those six preliminary experiments are shown in Fig. 2. Case02 and case 05, which are having a wave period of 1.25s showed most prominent converging circulations. Hence we have selected case 02 for the main set of experiments, which are outlined in Table 1.

Influence of wave period on strength of circulation

As seen from Fig. 2, the strength of the converging circulation currents is getting weakened as wave period increases (with respect to case 02 and case05). When relatively longer period waves are incident, they tend to break more shoreward and as a result, broken wave heights behind the submerged breakwaters become larger compared to short period waves. This feature also increases shoreward mass flux over the structure. The strong onshore-ward mass flux is compensated by strong return flow through the gap and this strong opposing current tends to block the waves, which are coming through the gap weakening the radiation stress forces through the gap. This feature eventually hinders the formation of secondary circulation pattern (convergence) near shoreline. At the same time the strength of the converging circulation currents is again getting weakened as wave period decreases (with respect to case 02 and case05). When relatively shorter period waves are incident, they tend to break more offshore-ward resulting insignificant difference in the wave radiation stress force through gap and that over the breakwater. This feature also weakens the converging circulations behind the breakwaters. As understood from these comparisons, circulation current patterns are highly sensitive to the balance between radiation stress, mean water level and onshore-ward mass flux over the structure, which indeed highly dependent upon period of the waves.

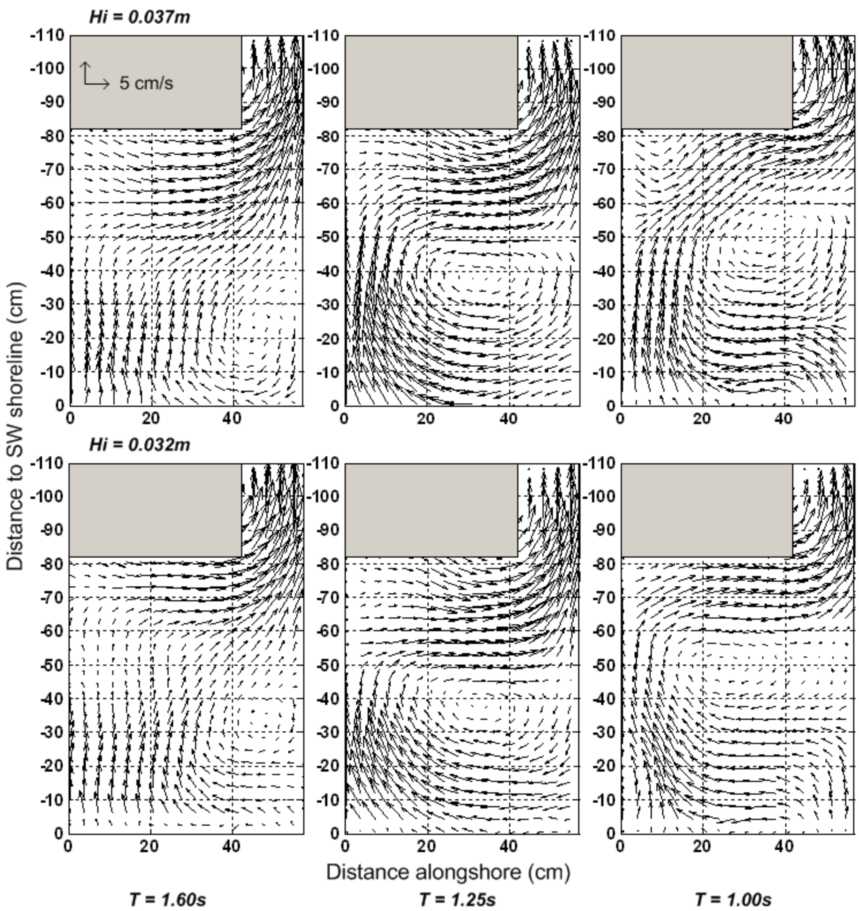

Figure 2. Spatial distributions of nearbottom current velocities associated with preliminary experiments.

CONCLUSIONS

A series of laboratory experiments were carried out to investigate the physical mechanisms of evolution of nearshore currents around submerged breakwaters. The strength of the converging circulations currents was found to be highly sensitive to the wave period. At the same time it showed dependency on the number of breakwaters and the gap between two adjacent breakwaters. Converging circulations were observed only in few cases with three submerged breakwater systems indicating limited range for application under given wave condition.

Laboratory experiments revealed that the converging circulations tend to be weakened or completely disappear at a particular gap width, when the return flow through the gap attains its maximum. This feature was more noticeable in infinite number of breakwater system. It should be noted that in designs this hazardous gap width to be avoided.

The use of anisotropic eddy viscosity coefficient in the breaking induced energy dissipation improved the predictive skills of the present model in simulating hydrodynamic features around a submerged breakwater system to a certain extent.

ACKNOWLEDGMENTS

This research was funded by a grant from JSPS (Japan Society for the Promotion of Science) Global COE (Center of Excellence) program entitled "Global Center for Sustainable Urban Regeneration"

REFERENCES

Dean, R.G., Chen, R., Browder, A.E. [1997] “Full scale monitoring study of a submerged breakwater, Palm Beach, Florida, USA,” *Coastal Engineering*, **29**, 291-315.

Deguchi, I., Sawaragi, T. [1986] “Beach fill at two coasts of different configurations,” *Coastal Engineering Journal,* **77**, 1032-1046.

Douglass, S.L., Weggel, J.R. [1987] “Performance of a perched beach - Slaughter beach, Delaware,” in *Proc. Coastal Sediments' 87.* ASCE, New York, USA, pp. 1385-1398.

Johnson, H.K., Karambas, T.V., Avgeris, I., Zanuttigh, B., Gonzalez-Marco, D., Caceres, I. [2005] “Modelling of waves and currents around submerged breakwaters,” *Coastal Engineering*, **52**, 949-969.

Kennedy, A.B., Chen, Q., Kirby, J.T., Dalrymple, R.A. [2000] “Boussinesq modeling of wave transformation, breaking and run-up, I:1D,” *Journal of waterways, Port, Coastal and Ocean Engineering*, ASCE, **126** (1), 39-47.

Larson, M., Kraus, N.C. [1991] “Numerical model of longshore current for bar and trough beaches,” *Journal of waterways, Port, Coastal and Ocean Engineering*, ASCE, **117** (4), 326-347.

Madsen, P.A., Sorensen, O.R., Schaffer, H.A. [1997] “Surf zone dynamics simulated by a Boussinesq type model, Part I. Model description and cross-shore motion of regular waves,” *Coastal Engineering*, **32**, 255-287.