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Effects of discontinuous submerged breakwater on water surface elevation

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Abstract. Submerged breakwaters are used to prevent shore line erosion and sediment transportation. One of their advantages is low visual impact. In this paper, the effects of discontinuous submerged breakwaters over water surface elevation was numerically studied considering the extended Boussinesq equations as governing equations using MIKE21 software. The result of discontinuous breakwater was compared with a beach without breakwater. The results showed that the gap dramatically effects on surface elevation from shore line to offshore. It is also evident from results that with approaching the center of the gap, fluctuation of surface elevation is generated. It is because of passing longshore currents towards offshore through the gap which leads to an increase in sediment transportation rate. Nevertheless, transferring water mass from breakwater gap results in powerful rip currents leading to high changes on longshore wave profile.

Keywords: submerged breakwater; Boussinesq equations; wave-breakwater interaction; rip currents

1. Introduction

As waves propagate towards shore line the transformation phenomena occurs related to sea bottom bathymetry changes. The length and the height of waves moving from deep water to shallow water change and as the wave slope goes over the critical limit and waves reach the breaking line they break and most of the wave energy releases. When high waves approaching the shoreline, water fluctuations occurs leading to beach erosion and sediment transportation. Therefore, preventing land erosion by wave attacks and decreasing the impact of inducing waves on shore structures are important subjects in coastal engineering.

Breakwater is a structure which is mainly used to protect the area in its lee from wave attack. In reality, the purpose of building breakwaters is providing a sheltered area for loading and offloading of the ships; as well as to manipulate the littoral transport conditions by trapping the moving sand particles. There are different types of breakwaters like detached breakwater that is completely isolated from shore and attached breakwater that is connected to the shoreline. Both of these types of breakwaters can be floating, emerged and submerged structures.

Today the use of detached low-crested or submerged breakwaters in conjunction with beach nourishment is advised for stabilization of beaches. This is mainly related to their small

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environmental effects combined with the obvious aesthetic advantages. They have also minimal impact on ship navigation. Such structures are invariably placed within the surf-zone and are attacked by breaking and broken waves. The submerged breakwater can cause waves to break in advance, which can induce large wave dissipation.

Many researchers studied the effects of submerged breakwater on waves. Johnson *et al*. (1951) found that over natural obstacles the energy was transmitted as a multiple crest system. Jolas (1960) observed harmonics of a simple wave on the lee side of breakwater in shallow water above a submerged shelf of rectangular section. The study of wave propagation over 2D obstacles was performed by Newman (1965). He showed that the submerged breakwater affect the wave by reflection and transmission.

Rojanakamthorn *et al.* (1989) presented a mathematical model for rectangular submerged breakwater. Mathematical study on wave interaction with a composite poroelastic submerged breakwater was made by Lan *et al.* (2014). Izumiya (1990) investigated the problem of wave propagation over a breakwater with different materials and presented a new analytical solution for description of the dynamic response of wave interaction with structure. Beji and Battjes (1993) performed numerical and experimental study on regular wave interaction with submerged breakwater. Losada *et al.* (1995) experimentally simulated the propagation of waves over a permeable submerged breakwater to examine the wave-induced flow in the porous media. Non-breaking solitary interaction with submerged permeable breakwater was studied experimentally and numerically by Wu and Hsiao (2013).They found that the magnitude of the turbulent intensity increases with increasing the solitary wave height at a constant depth and the measured turbulent intensities on the seaward side are larger than those on the lee side of the structure.

Seabrook (1997), Tsujimoto *et al*. (1999), Kawasaki and Iwata (1998) and Lin (2004) studied the performance of submerged breakwater. The values of wave reflection, transmission and dissipation (RTD) coefficients indicate the effectiveness of a submerged breakwater. Therefore researchers try to investigate this coefficient for submerged breakwater. The transmission of wave energy through submerged breakwaters was studied by several researchers in different ways (Abdul Khader and Rai 1980, Allsop 1983, Van der Meer and Daemen 1994). The damping action of rectangular submerged breakwater and expressing its transmission coefficient (K_t) in terms of the transmitted energy to the total power of the wave was studied by Raman *et al.* (1977). Haller *et al.* (1997) studied the horizontal circulation supported by a shore bar with a gap. They showed the existence of a circulation current which fluctuates in the horizontal plane. Created rip current move back towards offshore through the gap.

Lin (2007) simulated the interaction between solitary wave and rectangular submerged breakwater to determine RTD coefficients for different length and width of breakwater. In his study the role of energy dissipation was explored and it was noticed that it can dissipate up to 60 percent of the total energy. He found that although wave breaking reduces wave transmission, it has little impact on wave reflection and the energy dissipation is caused by vortex shedding. Young and Testik (2011) studied wave reflection by submerged vertical and semicircular breakwaters. They noticed that the submerged vertical breakwaters reflect more energy than submerged semicircular breakwaters for the same a/H ratio (*a*; the breakwater's depth of submergence and *H*; the height of the incident wave at the breakwater).

Other researchers focused on the effects of submerged breakwater on beach current (Haller *et al*. 2002, Liu *et al*. 2008 and Koraim *et al*. 2014). Nils *et al*. (2002) experimentally studied a rip channel flow on submerged breakwater. They showed that how the overall trajectory pattern changes as a function of the distance of the wave breaking from bar crest.

Belloti (2004) estimated the current intensity and the mean water levels in terms of geometrical parameters and wave characters around the discontinuous submerged breakwater. He tried to present a simplified model for estimating of these parameters between shoreline and barrier. Another study was performed on the condition of wave behind the submerged breakwater (Calabrese *et al*. 2006).

The study examined shadow zone circulation, including currents and seaward flows through a gap under the hypothesis of 2D motion.

Ranasinghe and Savioli (2010) studied the shoreline response to a single shore-parallel submerged breakwater. Sharif Ahmadian and Simons (2014) simulated a 3D numerical model of nearshore wave field behind structures which predict the spatial transmission coefficient for regular waves by a numerical method. Simulating and studying the effects of a gap on submerged breakwater have continued by researchers (Kevin *et al*. 2001, Hur *et al*. 2003, Carevic *et al*. 2013, Zhang *et al*. 2013).

The utilization of submerged breakwater due to preserving beauty of the coast has increased to prevent beach from erosion. As can be seen in broad literature review just a few researchers studied the discontinuous submerged breakwaters. Therefore in this paper, the effect of trapezoidal discontinuous submerged breakwater on water surface elevation was studied. This gap may be needed for passing ships. The effect of gap on surface elevation was studied by Boussinesq equation. At first, the governing equation and the ways they can be discredited were presented. Then the beach without breakwater was compared with the one with discontinuous submerged breakwater and the results were discussed.

2. Governing equations

To model the currents around the submerged breakwater, modified version of Mike 21 BW Software was used (DHI Sofware, 2014). In this module, the numerical model is based on 2D equations of the enhanced Boussinesq equations. They can be expressed in 1D or 2D conditions in terms of free surface elevation η and the depth-integrated velocity-components, P and Q. The Boussinesq questions are

Continuity equation

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

Momentum equation in X direction

$$n\frac{\partial P}{\partial t}+\frac{\partial}{\partial y}\left(\frac{pQ}{h}\right)+\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)+n^2gh\frac{\partial \eta}{\partial x}+\frac{\partial R_{xy}}{\partial x}+\frac{\partial R_{xx}}{\partial x}+F_X+n^2P\left[\alpha+\beta\frac{\sqrt{p^2+Q^2}}{h}\right]+$$
$$\frac{gP\sqrt{p^2+Q^2}}{h^2c^2}+n\Psi_1=0 \qquad (2)$$

Momentum equation in Y direction

$$n\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{pQ}{h}\right)+\frac{\partial}{\partial y}\left(\frac{Q^2}{h}\right)+n^2gh\frac{\partial \eta}{\partial y}+\frac{\partial R_{xy}}{\partial x}+\frac{\partial R_{xx}}{\partial x}+F_y+n^2Q\left[\alpha+\beta\frac{\sqrt{p^2+Q^2}}{h}\right]+$$

$$\frac{gQ\sqrt{p^2+Q^2}}{h^2c^2} + \mathrm{n}\Psi_2 = 0$$

Where Ψ_1 and Ψ_2 are the Boussinesq dispersion terms, F_x and F_y are the horizontal stress terms, h is total water depth and d is still water depth. C is Chezy resistance number and α *and* β are resistance coefficients for laminar and turbulent flow in porous media, respectively. n is the porosity of the media.

In Mike 21 BW Software, the FEM is used to solve the Boussinesq Equations (see Madsen *et al*. 1991). In this method, time-centered implicit scheme for differential equations is used while variables are defined on a space-staggered rectangular grid (Fig. 1). In this grid, water surface elevation is defined in the grid nodes. Components of P and Q are defined between adjacent grid nodes in the respective directions. The finite-difference approximation of the spatial derivatives and straightforward mid-centering used by the model are described in detail in Madsen and Sorenson (1992).

3. Model set up

To study the effects of discontinuous submerged breakwater on shore currents, a beach with a slope of 1:2.7 that is located at distance 200 m from shoreline (Fig. 2) was simulated. The size of model area was 1200 m * 1200 m which had a discontinuous submerged breakwater parallel to the beach line (Fig. 3). The gap was 100 m wide and the water depth on the breakwater crest was 2 m.

For wave generation a line of wave makers was modeled in offshore side of the study area. Before this line a sponge layer was located to absorb the waves (Fig. 4). The width of sponge layer was corresponding to the wave length. To dissipate the wave energy in areas where the surface roller is not eliminated and also for removing high frequency waves at the shoreline which created during uprush and downrush, a low pass filter was designed.

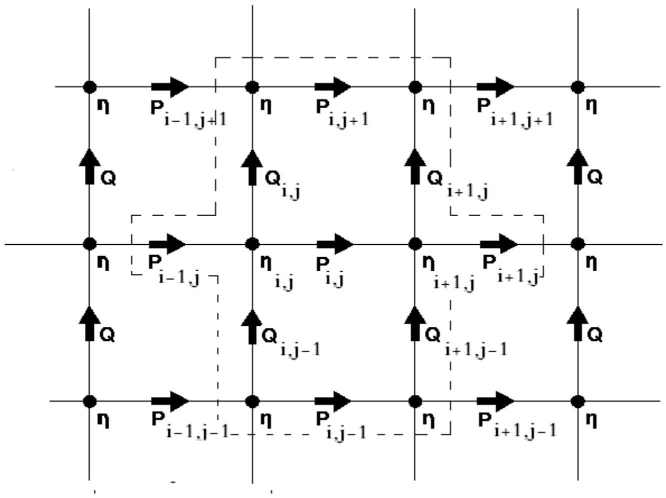

Fig. 1 Staggered grid notation in x-y space

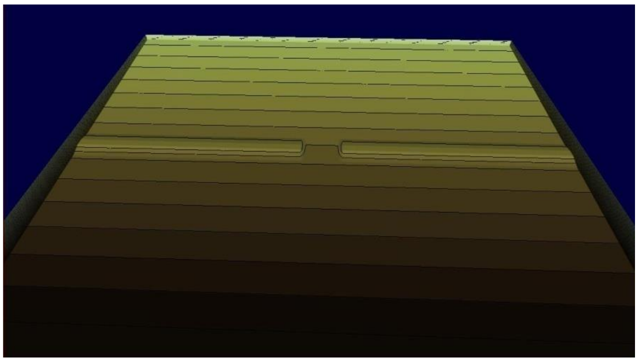

Fig. 2 The plan view of discontinuous submerged breakwater

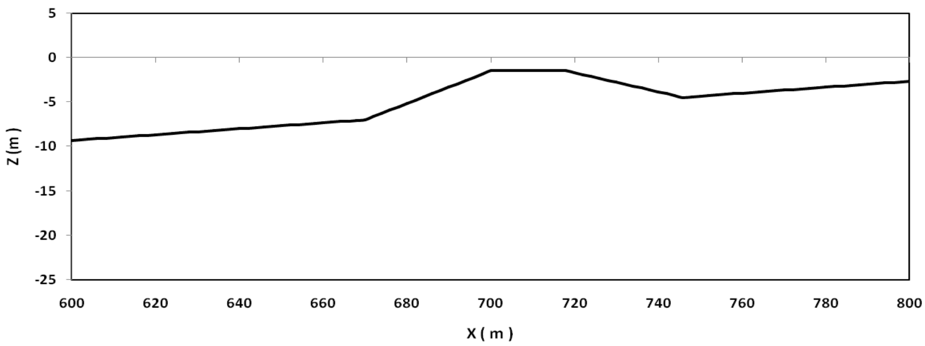

Fig. 3 A schematic of submerged breakwater surface

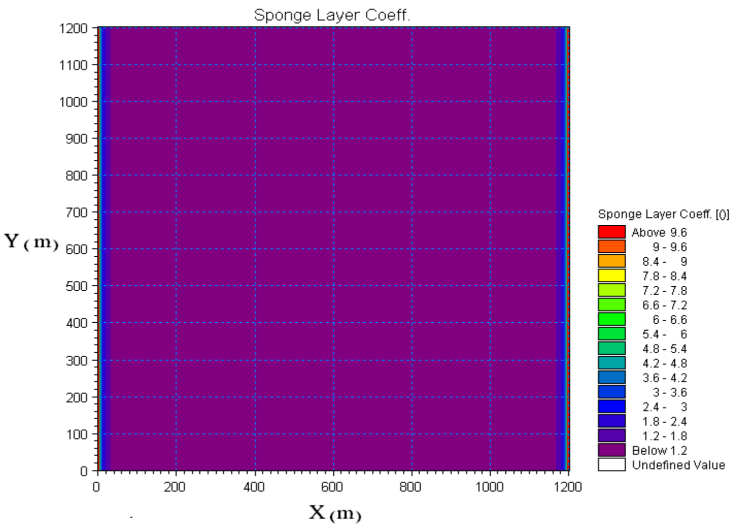

Fig. 4 Sponge layer Coefficient

4. Results and discussion

As waves approach the shoreline the wave height increases leading to wave break on breakwater. Fig. 5 shows the x-y coordinates selected for the study domain. To show the induced changes over incoming waves by the structure, especially near the gap, the water level changes was presented in Figs. 6 and 7 at time t = 9 to 11 sec. In beach without breakwater, the wave crests remain in parallel direction to shore (see Fig. 3).Waves break when they reach to the breaking point of the beach. However, discontinuous submerged breakwater causes a change in wave height as they approach the shore line. The variations in wave height are maximum at the center of the gap (see Fig. 7). This issue has shown the high effects of gap over the surface of incoming waves leading to a high irregularity.

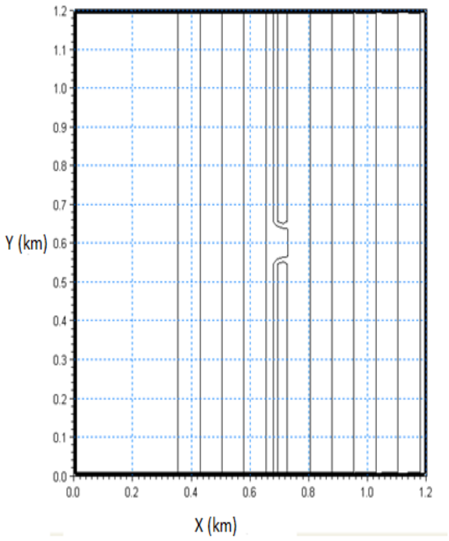

Fig. 5 The Cartesian coordinate system and its origin for the study area

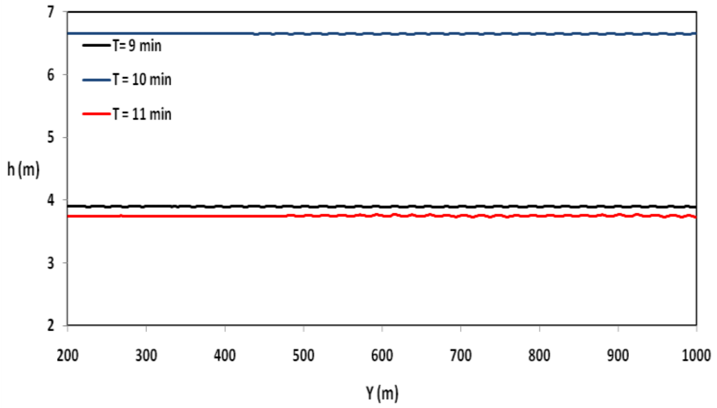

Fig. 6 Water depth elevation at point X= 740 m on beach in the lack of breakwater

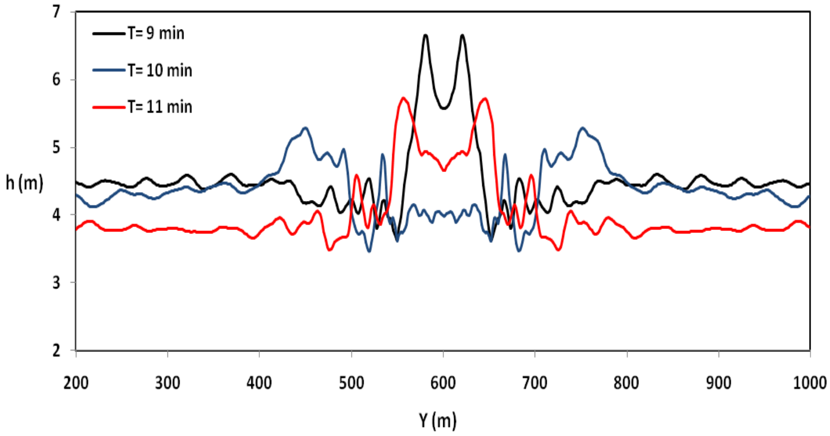

Fig. 7 Water depth elevation at point X= 740 m on beach in presence of discontinuous submerged breakwater

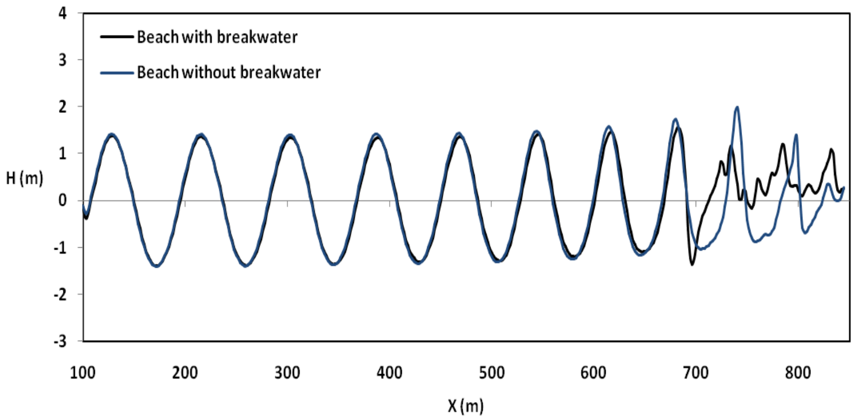

Fig. 8 Propagation of regular waves over the beach at point Y= 100 m

As water depth decreases, the wave height increases to a critical height and then the waves break. Hence, the height of incoming waves in two sides of the gap as getting close to the shore and reaching to the breakwater increases and break over breakwater (see Fig. 8). Broken waves accumulate in shore line and return towards offshore through submerged breakwater's gap. The movement of outflow towards offshore from the gap is known as rip currents. The rip currents are seaward-directed jets that originate within the surf zone and continue outside the breaking zone. The height of the incident waves encounter the rip currents is increased. Wave height changes in the center of the gap of the breakwater and in the same location without breakwater are shown in Fig. 6. It can be seen that as getting close to the shoreline, the wave height in the beach increases more than that of without breakwater. Point (470, 600) shows that this increase is appropriately while near the gap, the changes happen at point x = 680 m in presence of submerged breakwater.

Comparison of Figs. 5 and 6 shows that the presence of the gap with a width of 100 m causes an increase in the wave height when passing through the gap. It is also evident that the breaking point moves back towards offshore about 50 m in comparison with the beach without breakwater. The breaking point in the gap way is at point (700, 600). In fact the height of waves that are located in the way of rip currents movement increases due to interaction between rip currents and incoming waves.

However this behavior is somehow vacillatory. The wave height changes in the center of the gap is shown in Fig. 9. It is evident from this figure that as getting close to the shoreline, the wave height for the beach with discontinuous breakwater increases more than that of without breakwater.

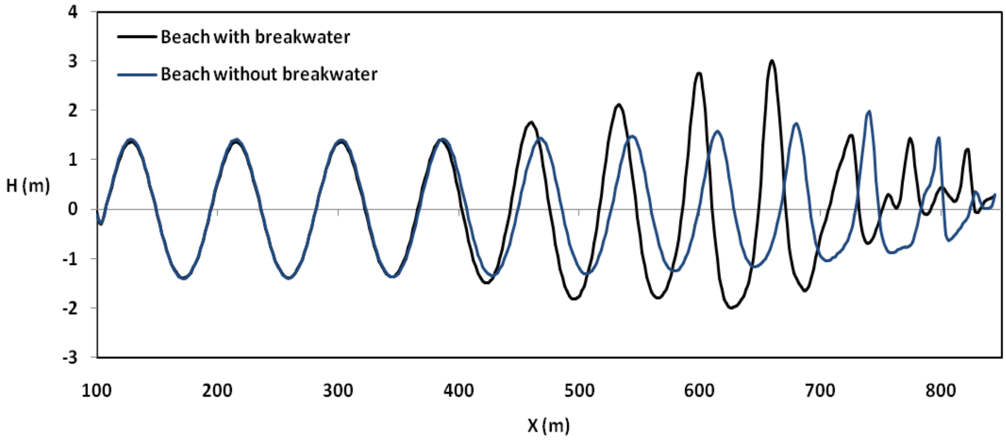

Fig. 9 Propagation of regular wave over beach at point Y= 600 m

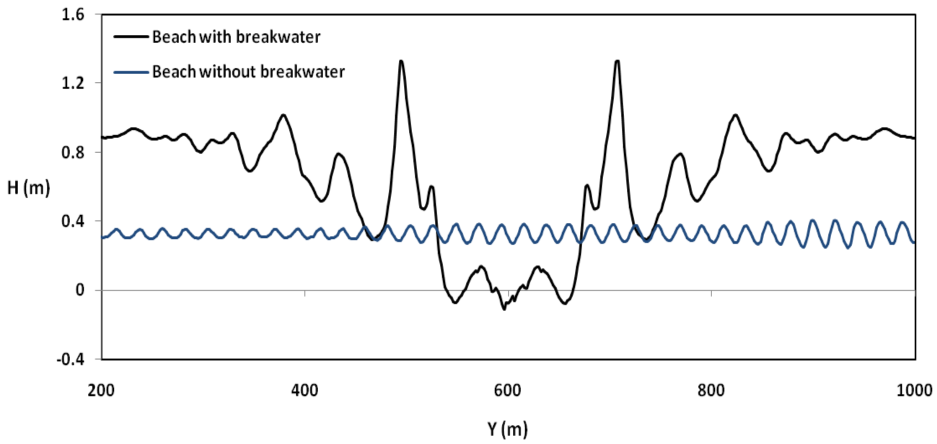

Fig. 10 Comparison of results of water level changes in the beach in lack of any structure and in presence of discontinuous submerged breakwater at point X = 830

Fig. 10 shows the changes in incoming wave structure near the shoreline where it interacts with rip current when it starts to initiate. Decrease of wave height from point y = 740 m to point y = 830 m is the evidence that current is parallel with the shore. These currents are known as longshore currents. They have the main role in generation of rip currents. Rip currents are dangerous for swimmer as they are created in shallow water near the shoreline. Also, generated fluctuations cause offshore sediment transfer by the flow motion. The sediment transportation not only culminates shore erosion but also change the color of water to muddy in rip currents head. The muddy water is the sign of the rip currents generated in the area.

5. Conclusions

The Boussinesq equations are used to simulate the regular waves in shallow water. Two cases i. e., beach without breakwater and beach with discontinuous submerged breakwater were studied. The results showed that the submerged breakwater gap plays an important role on shore currents pattern. The height of the incoming waves does not change intensely on two sides of the gap. However in the gap the wave height changes dramatically associated with some fluctuation. These changes are due to wave interaction with rip currents created by longshore currents in the study area. The longshore currents accumulate and return towards offshore through the gap. This changes water surface elevation and these effects continue to offshore. The movement of currents towards offshore causes the sediment transport from shore line, shoreline erosion and a threat for swimmers. Additional studies are needed on the transient rip currents, the effects of breakwater height changes over shore currents and the rate of sediment transportation around the discontinuous submerged breakwaters.

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