

Investigating the reactions of rip current pattern and sediment transport in rip channel against changes of bed parameters using numerical simulations

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This paper consists the effects of bed parameters changes on rip current pattern and sediment transport in channels by means of numerical simulations. Model predictions are compared with field observations showing a reasonable agreement. Results of this research show the general pattern of hydrodynamic current in the form of eddies with reverse vorticity along the sides of rip current, so that the rate of erosion along the rip channel and location of sedimentation towards the offshore zone are affected by these eddies. Present study shows that morphologic changes in rip channel have a direct relation with non-dimensional rip flow velocity ($\tilde{U}_r$) and changes in bed parameters, in a way that changes in non-dimensional cross-sectional flow area ($\tilde{A}$) are severely affected by the distance of bar from the shoreline and slope.

[**Keywords:** Rip currents, Eddies, Vorticity, Morphological changes, numerical simulations]

Introduction

Rip currents are intense, seaward-directed jets that spring out within the surf zone due to longshore gradients in wave-induced radiation stresses and pressure^{1,2,3}. These currents can play a significant role in transport of sediments towards sea and accordingly by morphologic changes of near shore zone, these currents are considered as a significant factor over circulation of the area^{4,5,6,7&8}.

Also the study of these currents is necessary due to the fact that they are considered as the main factor in drowning people who swim in the coastal water and due to the temporally and spatially variable behavior of the currents⁹. Despite the problems arising from the varying nature of these currents, a lot of field and experimental studies have been conducted on rip currents and their behavior at different seashores^{10, 11}. Many attempts by Gourlay¹² and Wright and Short¹³ have been conducted on the beaches state using Ω

beach under parameter with different hydrodynamic conditions. Based on the findings, rip currents are usually formed in beaches which are under intermediate states with $1 < \Omega < 6$. Regarding the effect of existence and persistence of rip currents on circulation of the nearshore zone, the pattern of sediment transport in the surf zone has been observed qualitatively for many decades^{14,15&16}.

Short and Brander¹⁷ attempted to correspond rip current spacing with average wave properties and sedimentary characteristics. They found weak correlation between rip spacing and wave height, surf zone width and wave period. Bühler and Jacobson¹⁸ reviewed the formation of eddies caused by the wave breakage in the bed with a longshore monotonous topography using numerical studies. They found that the behavior of big eddies caused by the wave breakage is basically related to the morphology of beach. Reniers *et al.*¹⁹ proposed that slowly evolving

eddy pairs are responsible for the formation of rhythmic rip channels.

Damgaard *et al.*²⁰ used a nonlinear hydrodynamic flow model coupled to sediment transport and morphology forced by normally incident monochromatic waves with a stochastic perturbation on bathymetry, and realized that rip channel spacing did not pertain to wave height, but did pertain to the width of the bar crest to shoreline. Kennedy *et al.*²¹ concluded that maximum cross-shore and longshore velocities are unresponsive to some details such as bar length. Large velocities noticed in the rip neck at startup are due to a strong primary vortex couple that grows in the rip neck whose velocity is decreased upon offshore migration of vortex couple.

MacMahan by field measurements, showed that low-energy waves can produce a rip current system over fine seashore bathymetric variations and discerned that rip current and corresponding morphology migrate alongshore^{22,23 and 24}. In recent years, some researchers as Bonneton²⁵ *et al.* have studied large-scale wave-induced vorticities in the surf zone using analytical approaches. They have also presented a new equation for mean current vorticity employing momentum equation and the nonlinear shallow water shock-wave theory.

Present work, through studying eddies' behavior, investigates the morphodynamic pattern of the surf zone exposed to bed parameters changes, and therefore paves the way for the studies concerning sediment transport under the different conditions dominating the bed. Results obtained in this research can be used for predicting the beach behavior varying with the changes of bed parameters, particularly in experimental studies concerning the rip currents in a movable bed. For this purpose, a barred beach with two rip current channels has been modeled using Mike 21/3 Coupled Model FM to study rip currents pattern and bed changes procedure. The study is structured as follows: In section 2, we describe the numerical model, domain conditions and different modules in the model. In section 3, we introduce near shore circulation and surf zone current pattern, and study

the effect of bed parameters changes on sediment transport in channel of the modeled beaches. In section 4, the results of numerical simulation are compared with field observations using non-dimensional rip current velocity in the entire bar-channel system, and finally the results are summarized in section 5.

Materials and Methods

Numerical model

Mike 21/3 Coupled Model FM is a dynamic modeling system which is used in coastal and estuarine zones. It can be applied for investigating the morphological advancement of near beach bathymetry due to the variable hydrodynamic conditions.

This model provides an approach to analyze the mutual interaction between waves and currents through dynamic coupling between the Hydrodynamic Module and the Spectral Wave Module. It can also model the process of full feedback among bed level changes caused by wave circulations through dynamic coupling between the Hydrodynamic Module, the Spectral Wave Module and the Sand Transport Module.

Hydrodynamic Module (HD)

In this research, a two-dimensional model in HD Module was used to investigate the wave-induced currents. The model is based on equations of shallow water in which the depth-averaged velocities of Navier-Stokes equations are integrated in an incompressible fluid.

The continuity equation and integration of horizontal momentum equations over depth $h = \eta + d$ can be obtained as:

$$\frac{\partial h}{\partial t} + \frac{\partial h\bar{u}}{\partial x} + \frac{\partial h\bar{v}}{\partial y} = hs \quad \dots(1)$$

$$\frac{\partial h\bar{u}}{\partial t} + \frac{\partial h\bar{u}^2}{\partial x} + \frac{\partial h\bar{u}\bar{v}}{\partial y} = f\bar{u}h - gh\frac{\partial}{\partial x} - \frac{h}{\rho_0}\frac{\partial p_x}{\partial x} - \frac{gh^2}{2\rho_0}\frac{\partial}{\partial x} + \frac{\tau_{xx}}{\rho_0} - \frac{\tau_{xy}}{\rho_0} - \frac{1}{\rho_0}\left(\frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial x}\right) + \frac{\partial}{\partial x}(hT_{xx}) + \frac{\partial}{\partial y}(hT_{xy}) + hu_x S \quad \dots(2)$$

$$\frac{\partial h\bar{v}}{\partial t} + \frac{\partial h\bar{v}^2}{\partial y} + \frac{\partial h\bar{u}\bar{v}}{\partial x} = f\bar{v}h - gh\frac{\partial}{\partial y} - \frac{h}{\rho_0}\frac{\partial p_y}{\partial y} - \frac{gh^2}{2\rho_0}\frac{\partial}{\partial y} + \frac{\tau_{xy}}{\rho_0} - \frac{\tau_{yy}}{\rho_0} - \frac{1}{\rho_0}\left(\frac{\partial s_{xy}}{\partial x} + \frac{\partial s_{yy}}{\partial y}\right) + \frac{\partial}{\partial x}(hT_{xy}) + \frac{\partial}{\partial y}(hT_{yy}) + hv_y S \quad \dots (3)$$

u and v are the depth-averaged velocities defined by:

$$h\bar{u} = \int_{-d}^0 u dz, \quad h\bar{v} = \int_{-d}^0 v dz \quad \dots(4)$$

The lateral stresses T_{ij} consists of viscous friction, turbulent friction, and differential advection which is estimated using an eddy viscosity formulation, based on depth average velocity gradients expressed by the following equation:

$$T_{xy} = A \left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x} \right), \quad T_{xy} = 2A \frac{\partial \bar{v}}{\partial y}, \quad T_{xx} = 2A \frac{\partial \bar{u}}{\partial x}, \quad \dots(5)$$

Where $h(x,y,t)$ is the depth of water; $\eta(x,y,t)$ is sea surface elevation; g is gravity acceleration; $p_a(x,y,t)$ is atmosphere pressure; ρ_w is the water density; s_{xx} , s_{xy} , s_{yx} and s_{yy} are components of the radiation stress tensor and (τ_{sx}, τ_{sy}) and (τ_{bx}, τ_{by}) are the x and y components of the surface wind and bottom stresses.

Sediment Transport Module (ST)

In this research, the method which is used in ST Module for calculation of sediment transport is based on the model of combined wave and current, and to do this the sediment transport tables for interpolation were used.

Spectral Wave Module (SW)

Spectral Wave formulation was used in this module, which is based on conservation equation of wave, defined by Komen²⁶ and Young²⁷ as:

$$\frac{\partial N}{\partial t} + \nabla \cdot (N \bar{v}) = \frac{S}{\sigma} \quad \dots(6)$$

Where, $N(x, y, , t)$ is the spectra density $\bar{v} = (c_x, c_y, c, c)$ is the propagation velocity of a wave group and S is the source term for the energy balance equation²⁸. The propagation velocities of a wave group have been achieved from below relations:

$$(c_x, c_y) = \frac{d \bar{x}}{dt} = \bar{c}_g + \bar{U} \quad \dots(7)$$

$$c = \frac{d}{dt} = \frac{\partial}{\partial d} \left[\frac{\partial d}{\partial t} + \bar{U} \nabla_x d \right] - c_g \bar{k} \cdot \frac{\partial \bar{U}}{\partial s} \quad \dots(8)$$

$$c = \frac{d}{dt} = \frac{-1}{k} \left[\frac{\partial}{\partial d} \frac{\partial d}{\partial m} + \bar{k} \cdot \frac{\partial \bar{U}}{\partial m} \right] \quad \dots(9)$$

Where s is the space co-ordinate in wave direction θ , and m is a co-ordinate perpendicular to s .

Model domain and its setup

In this work, a barred beach with two channels was examined. The existing computational domain has an extension $L_x = 700\text{m}$ in the cross-beach direction and $L_y = 1500\text{m}$ along the beach. The bar, with a cross-beach width of about 210 m, is located approximately 350 m offshore. Two channels, with a maximum width of 110 m, divide the bar in the viewed domain. The area under study was molded in an unstructured mesh which involves 4913 computation node and 9630 elements; moreover, the space between the grids in this model is about 5 m (Figs. 1 and 2).

A no-flow condition is imposed at the beach line. Boundary conditions are employed for the lateral boundaries at two sides of the area under investigation

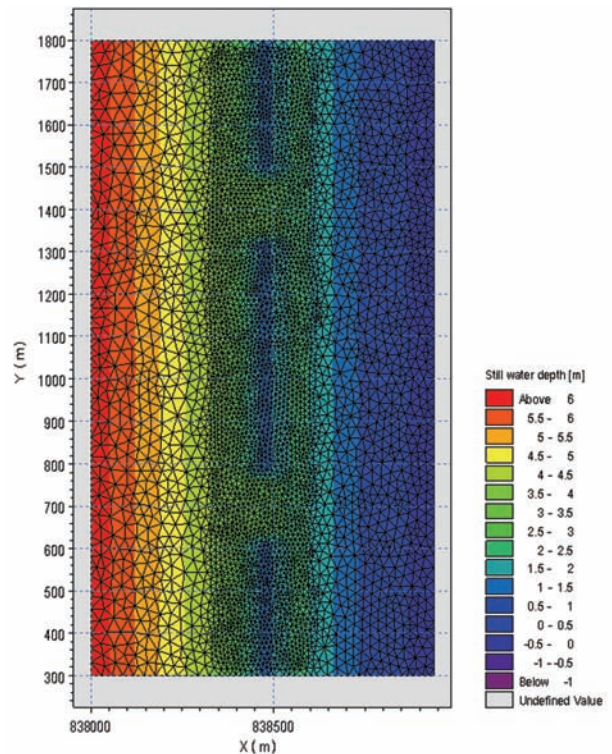


Fig. 1-Model computational domain.

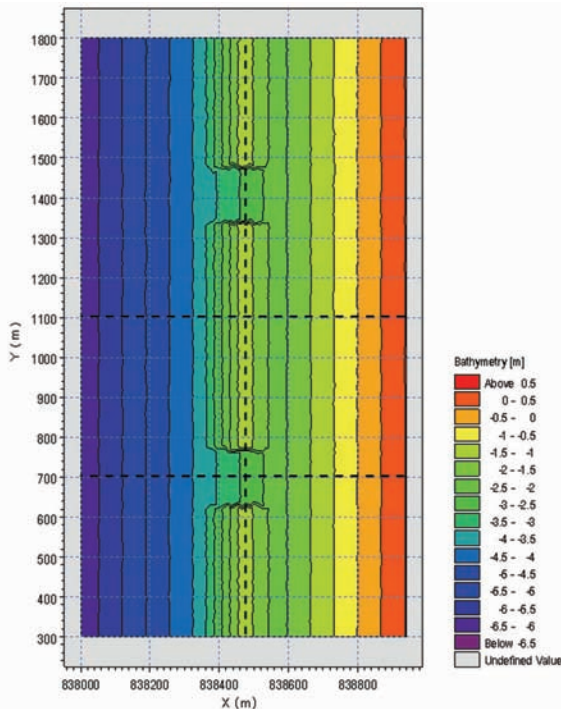


Fig. 2–Initial bathymetry with the studied lines.

in spectral wave module. Moreover, lateral boundary conditions are assumed as zero sediment flux gradient in sediment transport module.

For the steady state circulation, the model output for 12 hr was examined. To satisfy Courant Friedrich Levy condition, the time step used was one second. In hydrodynamic module, for the kind of bed resistance the fixed manning number $32 \text{ m}^{1/3}/\text{s}$ was chosen and the horizontal eddy viscosity was also chosen as $0.28 \text{ m}^2/\text{s}$. Moreover, in the Sand Transport Module, the wave and current effects are taken into account simultaneously. In Spectral Wave Module, the full spectral formation was applied in the formulation of stationary formulation. In this model, the effect of wind was also regarded in the lowest, while the bottom friction coefficient was considered variable for each state.

In this model, the hydrodynamic conditions are fixed while reviewing the effects of bed parameters' change on the beach, so that in all states waves with $H=2.2 \text{ m}$ and $T=7 \text{ s}$ was chosen and the direction of wave attack was considered normal to the shoreline.

Results and Discussion

Current pattern, erosion and sedimentation in rip channel

The experiment related to the formation of current pattern is first conducted on a beach with $C_f=0.004$, $gd=0.2 \text{ mm}$ and $\text{slope}=0.0075$ then the reactions of current pattern and sediment transport in rip channel are considered against the changes in bed parameters.

Based on the results of the model, wave-induced current moves towards channel on the beach normally, and while decreasing the depth of water, waves would break on the bed bars gradually. Whereas waves move in spaces between bars at the channel entrance without breaking and would break towards beach. When waves attack the beach, a nearly intense current induced by wave breaking would be formed on sand bars. However, this current was not formed in the spaces between the bars. This fact leads to formation of pressure gradient towards channel entrance. Thus, the formed rip current would be narrow, intense and nearly straight on the beach with a mushroom appearance. In general, these processes result in formation of seaward eddies with reverse vorticity at the channel entrance. The passing waves in channel entrance would also form weak eddies after breaking in surf zone; thus, stronger sea-directional eddies cause to increase the depth in distance between bars and beach and to decrease the depth in sea-directional entrance of the channel.

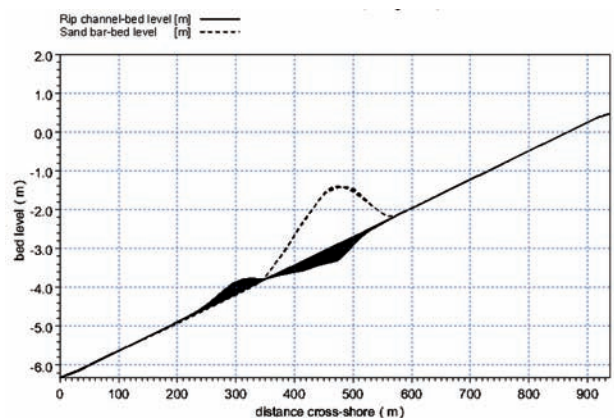


Fig. 3–The profile of bed level in rip channel ($y = 700 \text{ m}$) and on bar ($y = 1100 \text{ m}$) after 12 hr of integration.

The overall pattern of beach erosion and sedimentation is shown in Fig. 3 which shows the erosion of sediments through the channel and transport of these sediments towards the sea and finally their sedimentation during rip current return towards offshore zone at the entrance of rip channel. In this condition, rip current would have the maximum speed at entrance seaward of channel (Fig. 4).

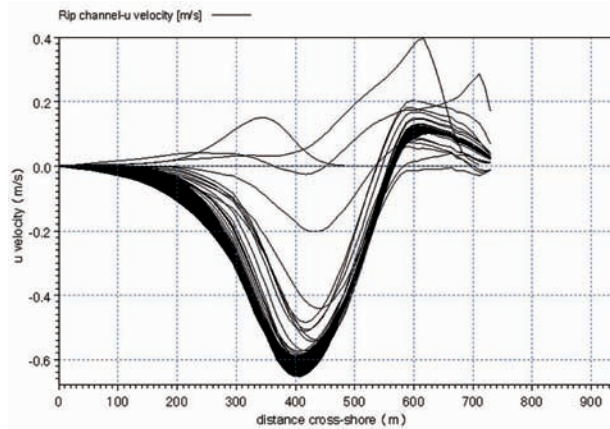


Fig. 4-The profile of change in velocity of cross-shore current on beach in rip channel ($y=700$ m) after with time.

Reaction concerning the variation of friction coefficient

The general pattern of current does not change by the change of bottom friction coefficient (BFC), but the sizes of eddies decrease by the increase of BFC. Hence, the sizes of eddies towards the sea in beaches having 0.4 for BFC, is much more fewer than the sizes of eddies towards sea in beaches having a value of 0.004 for this parameter (Fig. 5).

As the Fig. 6 shows by the decrease of sizes of eddies in beaches with more BFC ($C_f=0.4$), the transport of sediments to the offshore zone is decreased and the sediment is resided in shorter distance of the channel entrance than that of beaches with $C_f=0.004$. The study of bed level in alongshore section of the beach having different morphodynamic features based on Fig. 7 shows that by decreasing BFC to $C_f=0.004$ and $gd=0.2$ mm and slope=0.0075 in comparison with the other beaches having the same features and $C_f=0.4$, the width of rip channel is increased and the space between the rip channels is

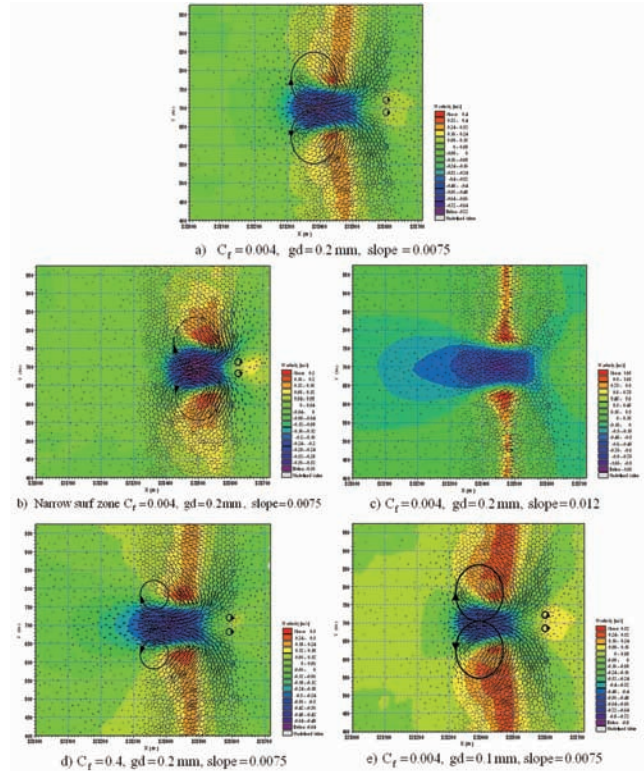


Fig. 5-The pattern related to the velocity of cross-shore current on beach after 12 hr for different parameters.

decreased while increasing the depth of channel.

Reaction concerning sediment size

The current pattern in beach having two sediment sizes, based on Fig. 5a and 5e in conditions

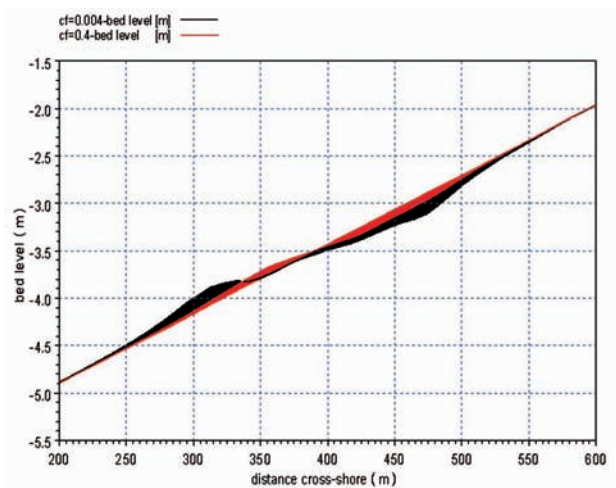


Fig. 6-The Profile of bed level in rip channel ($y=700$ m) in the beach having two different bottom friction coefficients after 12 hr.

in which the two beaches having the same hydrodynamic and morphodynamic features, shows that the current pattern is unchanged.

Thus beaches having sediments with different sediment sizes have the same pattern of erosion and sedimentation (Fig. 8), but as the comparison of bed level shows after 12 hr changes at the center of

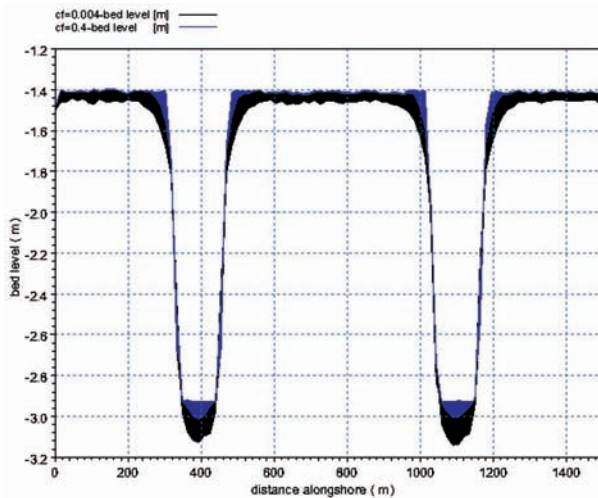


Fig. 7–The Profile of bed level ($x=838470$ m) in beach having two different bottom friction coefficients after 12 hr.

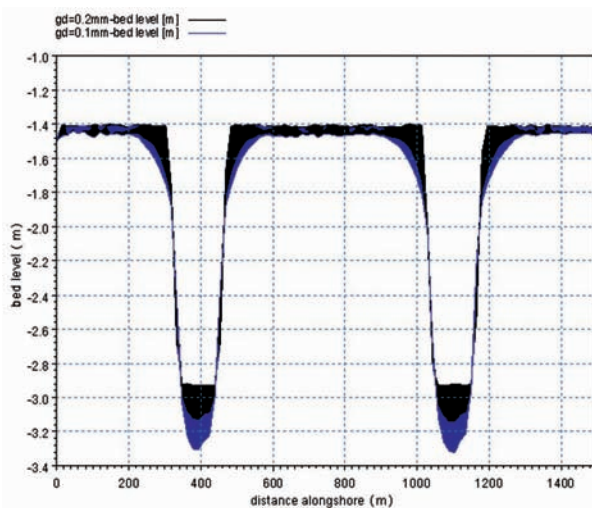


Fig. 8–The profile of bed level ($x=838470$ m) having two different sediment sizes after 12 hr.

channel, the smaller the sediment size having ($gd=0.1\text{mm}$), the more erosion and sedimentation in rip channel because intensity of eddies' action increases the transport of fine sediments and leads to increased erosion at the channel (Fig. 9).

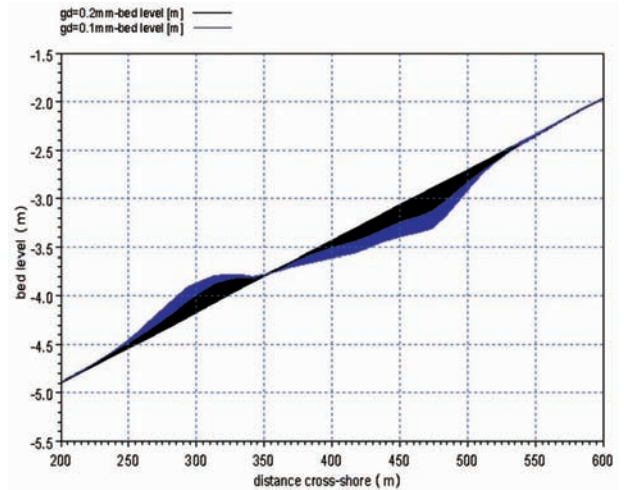


Fig. 9–The profile of bed level in rip channel ($y=700$ m) in beaches having two different sediment sizes after 12 hr.

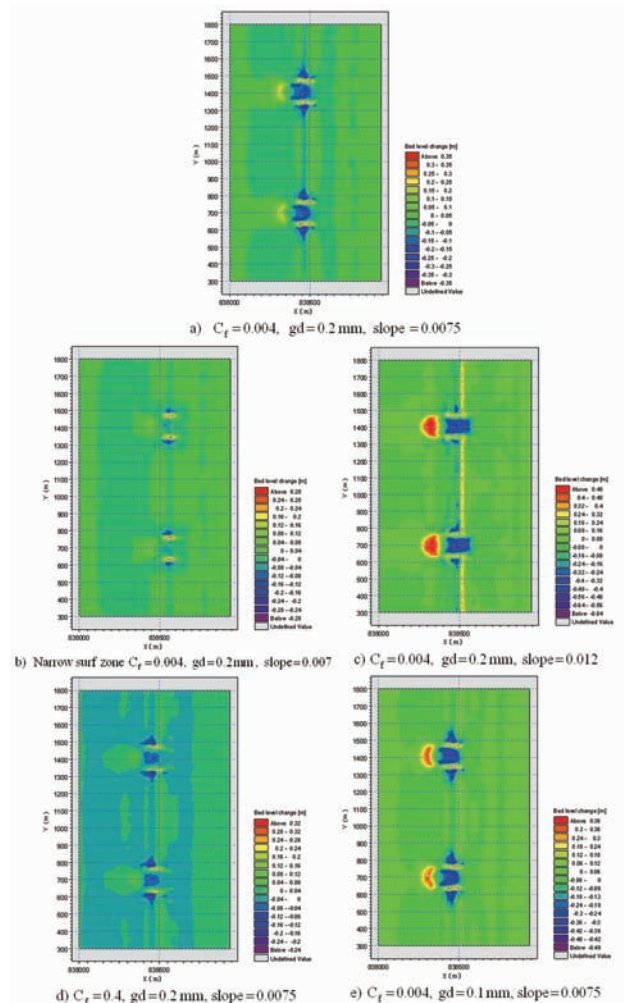


Fig. 10–The pattern of bed level change after 12 hr for different parameters

The bed level change of the beaches with sediments having two different sizes of $gd=0.2\text{mm}$ and $gd=0.1\text{mm}$, based on the Fig. 10a and 10e, shows non-changing of erosion pattern and sedimentation; but the rate of erosion and sedimentation in any area have direct relation with the size of the beach sediments.

Reaction concerning beach slope

The patterns of currents in beaches which have different slopes are constantly changing. So that the plan related to the speed and direction of normal current to the beach, having slope of 0.0075 indicates that the pattern of the current has a form of eddies with reverse vorticity on the sides of rip channel. However it is removed in beaches having the same features but a slope of 0.012 for eddies. The deletion of eddies in the current pattern change the bed level greatly that can be obviously seen in comparison of Fig. 12a and 12c. As it is observed in this figure, and as the profile of bed level at the center of channel in Fig. 11 shows, the rate of erosion in channel in beaches having a slope more than 0.012 is greatly increased in comparison with the beaches having a gentler slope.

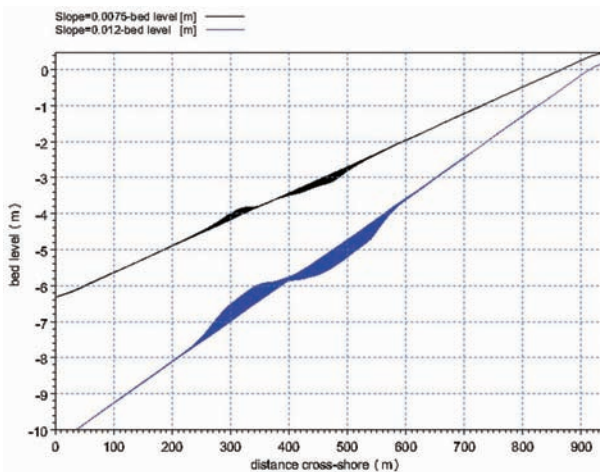


Fig. 11–The profile of bed level in the channel ($y=700\text{ m}$) in beaches having two different slopes after 12 hr.

In a beach with a higher slope, the rate of sedimentation at the entrance of channel increases. As it can be observed in Fig. 12, the width of rip channel also increases by increasing the bed slope 0.12 in comparison with a beach with gentler slope;

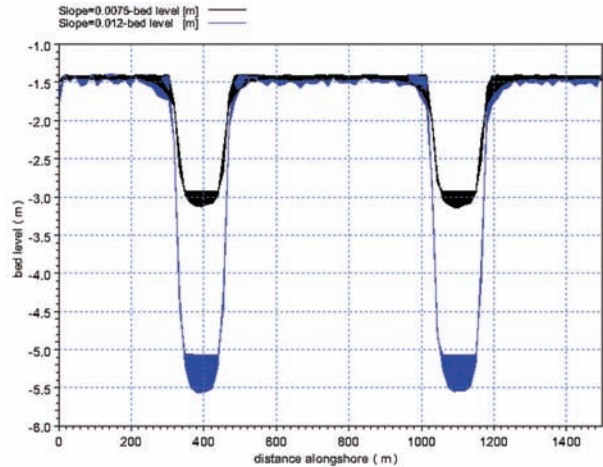


Fig. 12–The profile of bed level in the channel ($x=838470\text{ m}$) in beaches having two different slopes after 12 hr.

thus, the channels of rip current in beaches with higher slopes (the breadth of narrower surf zone) have higher width and the space between the channels also decreases.

Reaction concerning the variation of bar crest distance from the shoreline

A comparison between two beaches with the same slope while having a different distance of bar crest from the shoreline shows that these beaches which are subject to waves having the same height will have a different hydrodynamic and morphodynamic behavior based on a change in breaking point, thus in beaches having a narrower surf zone, the breaking point is nearer to the shoreline, hence the incoming wave passes more distance to arrive at the breaking line in the surf zone. Due to this, factors such as the bottom friction and effects caused by shoaling can cause wave dissipation in beach having a narrower surf zone due to the same slope in the beach. These factors cause that the power of waves and the rip current caused by the wave action on bar cannot decrease the channel longitudinal and latitudinal erosion during the same periods, whereas in a beach having broader surf zone, the breaking wave in farther distance of shoreline and the pressure gradient caused by the difference in height of broken waves along beach form a stronger rip current with fewer spaces (Fig. 13).

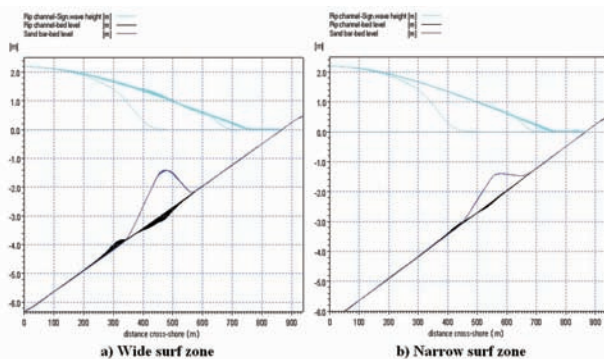


Fig. 13–The profile of bed level in rip channel ($y = 700$ m) on bar ($y = 1100$ m) in beaches with wide surf zone and narrow surf zone having two different breakage points after 12 hr.

The pattern of current in beaches having two areas of narrow and broad surf zone is almost the same and the presence of eddies is observed in both beaches (Fig. 5a and 5b).

Accordingly we can say that while the location of erosion and sedimentation in rip channel is not changed, the rate of erosion and sedimentation in the channel is decreased not only regarding the intensity of the weak performance of wave but also regarding the wave-current interaction on beaches in which the distance of bar crest is shorter from the shoreline; thus not only the slope of beach but also the distance of bar crest from the shoreline affects the rate of rip channel spacing more considerably, since based on Fig. 14 in beaches in which the distance of bar crest is less than the shoreline, the erosion of channel breadth and width is far less than the beach with the same slope in 12 hr of running program having larger distance of bar crest from the shoreline. Thus the

factor which increases the width of rip channel through erosion is not only the rate of wave energy but also the distance of bar crest from the shoreline, and this parameter is also one of the main factors related to the spaces among the rip currents channels.

Comparison of field observations and model experiments

To compare the results of the model with field observations, the results of Brander (1998) were used. He studied beaches in Palm Beach, Australia, based on the previous researchers' studies such as Wright and Short (1984) which were about rip currents with different states of beach.

Brander evaluated evolution of deposition in intermediate state and offered a relation as:

$$\tilde{u}_r = -18.6(\tilde{A}_r) + 17.6 \quad \dots(10)$$

Where $\tilde{u}_r$ is the non-dimensional rip flow velocity which has been non-dimensionalised by

$\frac{H_{rms}}{T}$, $\tilde{A}_r$ is the non-dimensional cross-sectional flow area.

He also evaluated the type of co-adjustment between morphology and speed of rip current. Given the fact that the aim of this research is to study the effects of bed parameters changes on current pattern and sediment transport in the coastal zone, values $\tilde{A}_r$ and $\tilde{u}_r$ were obtained after running the model for 12 hr over the beaches with different features in bed, as shown in Table 1.

Table1–Values of $\tilde{A}_r$ and $\tilde{u}_r$ calculated based on the results of the model for different beaches

Beach feature	Related features of bed parameters	$\tilde{A}_r$	$\tilde{u}_r$
A	$C_f = 0.004$, $gd = 0.2$ mm slope=0.0075, wide surf zone	0.69	2.87
B	$C_f = 0.004$, $gd = 0.2$ mm slope=0.0075, narrow surf zone	0.9	2
C	$C_f = 0.004$, $gd = 0.2$ mm slope=0.0075, wide surf zone	0.81	2.53
D	$C_f = 0.004$, $gd = 0.2$ mm slope=0.0075, wide surf zone	0.77	2.84
E	$C_f = 0.004$, $gd = 0.2$ mm slope=0.0075, wide surf zone	0.67	2.88

However, the results obtained for a specific area in this research were compared with those obtained by Brander and presented in Fig. 15.

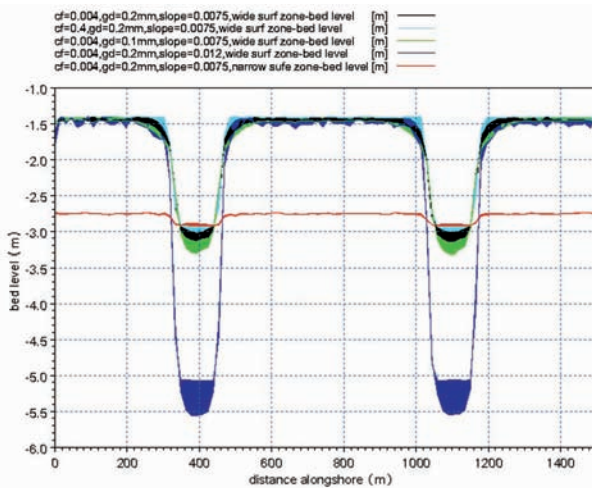


Fig. 14–The profile of bed level in $x=838470$ m in beaches with different features in bed after 12 hr.

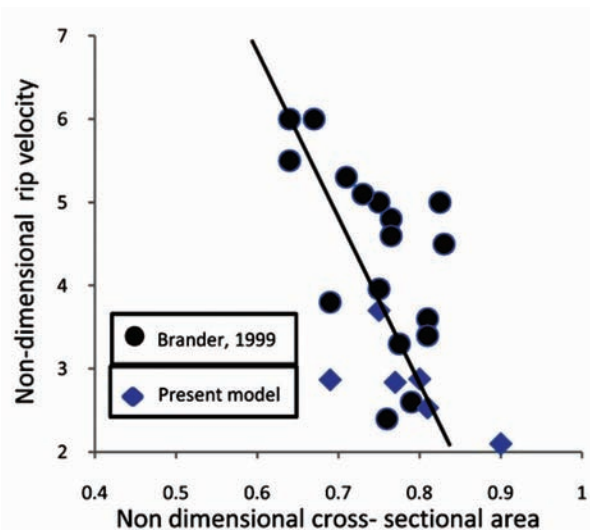


Fig. 15–Changes of non-dimensional rip flow velocity in non-dimensional cross-sectional flow area and comparison of results from the model with those from Brander's field observations.

Selecting beach A as the source beach, the rate of change in parameters $\tilde{A}_r$ and $\tilde{u}_r$ is easily observed with the change in bed parameters. Based on the obvious difference in parameter $\tilde{A}_r$ in beaches A and B and in comparison with other beaches, it is shown that changing the space between bar crest and beach

line is the most important factors in changing non-dimensional cross-sectional flow area. The comparison of values related to non-dimensional rip flow velocity in different beaches according to Table 1 shows the mutual relationship between $\tilde{A}_r$ and $\tilde{u}_r$ in the beaches under review based on relation (10). Since the time of running program is short, the limit of changes in $\tilde{A}_r$ and is so limited in comparison with the results of Brander studies.

Table1–Values of $\tilde{A}_r$ and $\tilde{u}_r$ calculated based on the results of the model for different beaches

Conclusion

Present study implies that rip current pattern, in the presence of different hydrodynamic and morphodynamic conditions, proves the existence of eddies with reverse vorticity on both sides of the rip channel in most cases. The change in size of sediments and the distance between shoreline and bar crest only changes the rate of sediment transport in rip channel and hence changes the depth of channel, whereas this does not affect the current pattern and the sediment transport towards offshore zone. However, the change of parameters such as beach slope and bottom friction coefficient changes the current pattern and weaken intensity of eddies' action or remove them, and transport the sediments towards offshore zone while it also changes the depth of channel. Bed parameters including beach slope, sediment size and bottom friction coefficient, depending on their significance, are considered as the important factors affecting the rate and process of erosion and sedimentation in a rip channel.

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