EFFECTS OF ANTHROPOGENIC FACTORS ON DEVELOPMENT OF SAND SPITS AND CUSPATE FORELANDS WITH RHYTHMIC SHAPES

M. Serizawa $^1$, T. Uda $^2$ and S. Miyahara $^1$

ABSTRACT: The development of sand spits and cuspate forelands with rhythmic shapes was numerically predicted using the BG model (a 3-D model for predicting beach changes based on Bagnold’s concept) under the oblique wave incidence that the angle between the direction normal to the shoreline and the wave direction is ± 60°, given an infinitesimal perturbation as the initial condition. Then the effects of the anthropogenic factors such as the construction of a groin and an offshore breakwater on the development of sand spits and cuspate forelands were investigated using the same model. The construction of a groin had a considerable impact on the sandy beach: the alteration from the field with the development of the sand spits to that with the elongation of a single sand spit, as well as the acceleration of offshore sand transport because of the blockage of longshore sand transport. The construction of an offshore breakwater strengthened the wave-sheltering effect as well as the blockage of longshore sand transport, resulting in dominant beach changes. The calculated results in the case of an offshore breakwater reasonably explained the example of the formation of the sand bars with two lagoons inside observed in a shallow lagoon surrounded by the Black Sea and Azov Sea.

Keywords: Sand spit, cuspate foreland, beach changes, BG model, anthropogenic factors, groin, breakwater

INTRODUCTION

Zenkovich (1967) showed that multiple sand spits with rhythmic shapes may develop in a shallow water body by the example in the Azov Sea, and concluded that under an oblique wave incidence with the angle between the direction normal to the shoreline and the wave direction being larger than 45°, shoreline instability may develop with the self-organization mechanism, and during the development of sand spits, the wave-sheltering effect due to the sand spits themselves plays an important role. Ashton et al. (2001) adopted this mechanism in their model and successfully modeled this shoreline instability using the upwind scheme in their different difference method. In addition, Ashton and Murray (2006) called this mechanism high-angle wave instability. Serizawa et al. (2012) showed that the 3-D beach changes of sand spits and cuspate forelands with rhythmic shapes can be predicted using the BG model (a 3-D model for predicting beach changes based on Bagnold’s (1963) concept). In previous studies, predictions were made only for the beach changes under natural conditions with no artificial structures, and the impact of the construction of the structures on the beach changes has not yet been investigated. Here, the effects of the construction of a groin and a breakwater on the development of sand spits and cuspate forelands with rhythmic shapes were investigated using the BG model.

METHOD

As the sand transport equation, Eq. (1) was used with an additional term to evaluate the increase in longshore sand transport owing to the effect of the longshore gradient of wave height (Ozasa and Brampton, 1980) on longshore sand transport, similar to that in Serizawa et al. (2012).

\[ \vec{q} = C_0 \frac{p}{\tan \beta_e} \left\{ K_e (\tan \beta_e \vec{e}_w - \cos \theta \vec{V}) \right\} \]

Here, \( \vec{q} = (q_x, q_y) \) is the net sand transport flux, and \( Z \) is the seabed elevation with reference to the still water level (\( Z = 0 \)). \( n \) and \( s \) are the local coordinates taken normal and parallel to the contour lines, respectively. \( \vec{V} = (\partial Z/\partial \alpha, \partial Z/\partial \beta) \) is the slope vector, \( \vec{e}_w \) is the unit vector of wave direction, \( \vec{e}_s \) is the unit vector parallel to the contour lines, \( \alpha \) is the angle between the wave direction and the direction normal to the contour lines. \( \tan \beta = \sqrt{\nabla Z} \) is the seabed slope, and \( \tan \beta_e \) is the equilibrium slope which mainly depends on the grain size of bed materials. \( \vec{e}_s \) is the unit vector of surf zone, \( \vec{H} \) is the gradient of wave height \( H \), and \( K_e, K_c, K_s \) are the coefficients of longshore and cross-shore sand transport, \( K_2 \) is the coefficient of Ozasa and Brampton’s (1980) term, and \( \vec{V} = \vec{e}_s \cdot \nabla H \) is the gradient of wave height \( H \) measured along the direction parallel.
Table 1 Calculation conditions.

<table>
<thead>
<tr>
<th>Wave conditions</th>
<th>Incident waves: ( H_i = 1 \text{ m}, \ T = 4 \text{ s} ), wave direction of 60° relative to normal to initial shoreline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berm height ( h_b )</td>
<td>1 m</td>
</tr>
<tr>
<td>Depth of closure ( h_c )</td>
<td>4 m</td>
</tr>
<tr>
<td>Equilibrium slope</td>
<td>( \tan \beta_e = 1/20 )</td>
</tr>
<tr>
<td>Angle of repose slope</td>
<td>( \tan \beta_g = 1/2 )</td>
</tr>
<tr>
<td>Coefficients of sand transport</td>
<td>( K_s = 0.2 ) coefficient of longshore sand transport, ( K_o = 1.62K_s ) coefficient of Ozasa and Brampton (1980) term, ( K_n = 0.17 ) coefficient of cross-shore sand transport</td>
</tr>
<tr>
<td>Mesh size ( \Delta x = \Delta y = 20 \text{ m} )</td>
<td></td>
</tr>
<tr>
<td>Time intervals ( \Delta t = 0.5 \text{ hr} )</td>
<td></td>
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<tr>
<td>Duration of calculation</td>
<td>1.5 \times 10^4 \text{ hr} (3 \times 10^5 steps)</td>
</tr>
<tr>
<td>Boundary conditions</td>
<td>Shoreward and landward ends: ( q_i = 0 ), right and left boundaries: periodic boundary</td>
</tr>
<tr>
<td>Calculation of wave field</td>
<td>Energy balance equation (Mase, 2001) ( \frac{\partial Z}{\partial t} + \nabla \cdot q = 0 ) were solved on the ( x-y ) plane by the explicit finite-difference method using the staggered mesh scheme. In estimating the intensity of sand transport near the berm top and at the depth of closure, the intensity of sand transport was linearly reduced to 0 near the berm height or the depth of closure to prevent sand from being deposited in the zone higher than the berm height and the beach from being eroded in the zone deeper than the depth of closure.</td>
</tr>
</tbody>
</table>

Here, \( f_D \) is the energy dissipation rate, \( E \) is the wave energy, \( K \) is a coefficient expressing the intensity of wave dissipation due to breaking, \( h \) is the water depth, \( \varphi \) is the ratio of the critical wave height to the water depth on a flat bottom, and \( \varphi \) is the ratio of wave height to the water depth \( H/h \). In addition, a lower limit was set for the water depth \( h \) in Eq. (3), similarly to that in the case of Serizawa and Uda (2011).

In the calculation of the wave field in the wave run-up zone, an imaginary depth was assumed as in the case of Serizawa and Uda (2011), and the wave energy at locations with elevations higher than the berm height was set to 0. In the numerical simulation of beach changes, the sand transport and continuity equations \( (\partial Z/\partial t + \nabla \cdot q = 0) \) were solved on the \( x-y \) plane by the explicit finite-difference method using the staggered mesh scheme. In estimating the intensity of sand transport near the berm top and at the depth of closure, the intensity of sand transport was linearly reduced to 0 near the berm height or the depth of closure to prevent sand from being deposited in the zone higher than the berm height and the beach from being eroded in the zone deeper than the depth of closure.

**CALCULATION CONDITIONS**

The formation of sand spits and cuspate forelands with rhythmic shapes was predicted first under the same conditions as in Serizawa et al. (2012), and then a groin or a breakwater was installed. The incident wave height \( H_i \) and the period \( T \) were assumed to be 1 m and 4 s, respectively. Five cases of calculation were carried out with the installation of a groin of 800 m length or an offshore breakwater of 600 m length. In Cases 1 and 2, a groin or a breakwater was placed at the center of the calculation domain, respectively, after the development of sand spits under the condition that waves were obliquely incident from the left with an angle of 60°. In Cases 3 and 4, in which waves are incident with an angle of \( \pm 60° \) and the probability of 0.5:0.5, a breakwater was placed offshore of the apex or the bay of the cuspate forelands, respectively. In Case 5, a breakwater was installed under the condition that waves are incident with an angle of \( \pm 60° \) and the probability of 0.65:0.35. The wave direction was randomly determined on the basis of the probability distribution at every step of the calculation of the wave field. The lengths of the groin and breakwater were determined, taking both the scale of sand spits and cuspate forelands and the wave diffraction effect of the structures into account.

\[ P = \Phi_{\text{all}} \] (2)

\[ \Phi_{\text{all}} = f_D E = K \sqrt{g/h} \left[ 1-(f/\varphi)^2 \right] E \quad (f_D \geq 0) \] (3)
For the initial bathymetry, a model beach with a constant depth of 4 m, a berm height of 1 m and a uniform slope of 1/20 was considered. A random perturbation with $\Delta Z = 0.5$ m was applied to this uniform slope as the initial condition. The calculation domain was a rectangular area of 4 km length and 1.2 km width, and periodic boundary conditions were set at both ends. The depth of closure was assumed to be $h_c = 4$ m and the equilibrium slope was 1/20. The coefficient of longshore and cross-shore sand transport was assumed to be $K_s = K_n = 0.2$. The calculation domain was divided by meshes with $\Delta x = \Delta y = 20$ m, and $\Delta t$ was set to 0.5 hr. The calculation with no structures was carried out up to $3 \times 10^4$ steps, and then the beach changes up to an additional $3 \times 10^4$ steps were predicted after the installation of the structures. The wave field was obtained at every 10 steps of the calculation of beach changes. Table 1 shows the calculation conditions.

RESULTS OF NUMERICAL SIMULATIONS

(1) Effect of Groin (Case 1)

The beach changes until $3 \times 10^4$ steps were calculated under the conditions that waves are obliquely incident from the direction of $60^\circ$ and then a groin of 800 m length and 4 m point depth was installed across the central sand spit after the sand spits have fully developed owing to the shoreline instability (Fig. 1(a)). These sand spits have developed while moving rightward, and the sand spit that moved out of the right boundary enters again from the left boundary as it is because of the periodic boundary condition at both ends. Figures 1(b)-1(j) show the results.

After $2 \times 10^3$ steps, the sand spit located left of the groin connected to the groin with a lagoon inside, whereas erosion started right of the groin because rightward longshore sand transport was obstructed by the groin. After $4 \times 10^3$ steps, part of the sand blocked by the groin started to be transported to the right while turning around the tip of the groin. The same situation continued after $6 \times 10^3$ steps, and a sand spit was formed owing to the deposition of sand turning around the tip of the groin up to $8 \times 10^3$ steps. Furthermore, as a result of sand discharge to the area right of the groin between $4 \times 10^3$ and $8 \times 10^3$ steps, the volume of sand left of the groin decreased, and the location of the starting point P of sand bar approached the groin with time, resulting in the decrease in the scale of the lagoon behind the sand bar. Until $1 \times 10^4$ steps, the sand spit formed at the tip of the groin elongated rightward along with the reduction in the scale of the sand bar left of the groin. After $1.5 \times 10^4$ steps, the sand spit extending from the tip of the groin

Fig. 1 Deformation of sand spits formed under oblique wave incidence from $60^\circ$ after extension of a groin
became a flying spit (Bird, 2000; Davis and FitzGerald, 2004) because of the reduction in sand supply by longshore sand transport. Because the flying spit is an unstable topography, it rapidly disappeared until \(2 \times 10^4\) steps. Then, because of the increased sand supply owing to the connection of another sand spit to the groin, a sand spit elongated obliquely from the tip of the groin until \(3 \times 10^4\) steps. It was realized from the comparison of Figs. 1(a) and 1(j) that sand was deposited, forming a steep slope along the shoreline on the exposed side, but the water depth generally decreased in the offshore zone owing to the sweeping motion of the sand spit, causing offshore sand movement. On the other hand, sandy beach with a gentle slope was formed in the lee of the sand spits and six branches were formed behind the sand spit. It is clear that the longshore sand transport was pushed seaward by the construction of a groin.

(2) Effect of Breakwater (Case 2)

The beach changes until \(3 \times 10^4\) steps were calculated under the conditions that waves were obliquely incident from the direction with an angle of 60° to the direction normal to the shoreline, and then a breakwater of 600 m length was installed offshore of sand spit A after the full development of sand spits owing to the high-angle wave instability (Fig. 2(a)). After \(2 \times 10^3\) steps, sand spit A behind the breakwater was eroded, because it was fully included in the wave-shelter zone of the breakwater so that rightward longshore sand transport was reduced. The same situation continued after \(4 \times 10^3\) steps and the rest of the sand of sand spit A was obliquely transported landward, and sand spit A disappeared while leaving the outline of the sand spit. During the period, sand spit B further extended to the lee of the breakwater.

The beach changes continued up to \(6 \times 10^3\) steps and the volume of sand deposited behind the breakwater increased along with the shoreline recession on the downcoast of the breakwater. After \(8 \times 10^3\) steps, a large tombolo was formed by the trapping of sand. After \(1 \times 10^4\) steps, another sand spit, which elongated from the left end, extended to connect the tombolo behind the breakwater. After \(1.5 \times 10^4\) steps, a continuous sand bar developed from the left end to the breakwater. Then, a small sand spit started to emerge at the right end of the breakwater by \(2 \times 10^4\) steps. After \(3 \times 10^4\) steps, the sand spit extended from the right end of the breakwater further elongated, even though the volume of sand deposited behind the breakwater did not change. Thus, the construction of the breakwater had a considerable impact on the beach; otherwise, sand spits developed with the self-organization mechanism. It is realized that

Fig. 2 Deformation of sand spits formed under oblique wave incidence from 60° after construction of a breakwater
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once a tombolo is formed behind the breakwater, offshore sand movement is enhanced owing to the presence of the breakwater and the tombolo, which blocks longshore sand transport.

(3) Effect of Breakwater (Case 3)

When waves are obliquely incident with an angle of ±60° to the direction normal to the shoreline with the probability of 0.5:0.5, cuspate forelands develop by $3 \times 10^4$ steps. This bathymetry, as shown in Fig. 3(a), was selected as the initial topography. Here, the cuspate foreland formed at the center is designated as A along with cuspate forelands B and C on the left and right, respectively. Then, a breakwater was placed offshore of cuspate foreland A, and the calculation was made until $4 \times 10^4$ steps. Under this condition, an symmetric wave-shelter zone was formed on both sides of the breakwater. The slender sand spits started to extend toward the lee of cuspate foreland A after 5 × 10^3 steps. These sand spits were asymmetric with the sand spit being larger size at cuspate foreland B.

Figure 4 shows the wave field after approximately 5 × 10^3 steps when waves are incident from the right and left, for example. Because the breakwater is placed offshore of cuspate foreland A and the distance between cuspate forelands A and B is shorter than that between cuspate forelands A and C, cuspate foreland B is subjected to an intensive wave-sheltering effect by the breakwater and cuspate foreland A under the condition that waves are incident from the right, whereas cuspate foreland C is located outside the wave-shelter zone by the breakwater and cuspate foreland A under the conditions that waves are obliquely incident from the left. Thus, the intensive wave-sheltering effects by the breakwater appeared at cuspate foreland B, resulting in the increase in the formative velocity of the sand spit near the tip of the cuspate forelands. Furthermore, in Fig. 3(b), cuspate foreland A protruded more than that under the initial condition. The same changes continued until 1 × 10^4 steps with rapid elongation of the sand spit at the tip of cuspate foreland B to the lee of the breakwater and it almost connected to cuspate foreland A. After 1.5 × 10^4 steps, the sand spit elongated from the tip of cuspate foreland B connected to cuspate foreland A and a barrier was formed with a lagoon inside. The scale of the sand
spit formed at the tip of cuspate foreland C also increased. After $2 \times 10^4$ steps, cuspate foreland B was entirely eroded, leaving a barrier island with a straight shoreline and a tombolo was formed behind the breakwater. No beach changes occurred inside the lagoon since then. On the right side of the breakwater, a sand spit elongated leftward with many branches to cuspate foreland A. After $2.5 \times 10^4$ steps, the tombolo behind the breakwater further developed and a lagoon was formed behind the barrier. Finally, after $4 \times 10^4$ steps, a large tombolo was formed with two water bodies inside the sandy beach behind the breakwater, the cuspate forelands with rhythmic shapes markedly deformed, and marked beach changes were induced by the wave-sheltering effect of the breakwater.

(4) Effect of Breakwater (Case 4)

The bathymetry with four cuspate forelands was selected as the initial bathymetry, as shown in Fig. 5(a), and a breakwater was placed offshore of cuspate forelands A and B. Beach changes until $4 \times 10^4$ steps were predicted under the condition that waves were obliquely incident from the direction of $\pm 60^\circ$ normal to the shoreline with the probability of 0.65:0.35. Then, an offshore breakwater was constructed in a zone offshore of sand spits A and B, and beach changes were calculated until $4 \times 10^4$ steps. The calculation results are shown in Fig. 6. Figure 7 shows the wave field after approximately $5 \times 10^3$ steps when waves are obliquely incident from the right and left. Because not only the probability of each wave direction is not equal as 0.65:0.35 but also sand spit B is located closer to the breakwater than sand spit C, an extremely asymmetric wave field was formed. Sand spit C was barely subjected to the wave-sheltering effect by the breakwater, whereas sand spit B effectively entered into the wave-shelter zone of the breakwater under the wave incidence from the left. Moreover, sand spit A was subjected to receive a strong wave-sheltering effect by the breakwater because of its proximity to the breakwater.

Owing to these reasons, the tip of the sand spit A

![Fig. 5](image-url) Deformation of cuspate forelands formed under the condition of oblique wave incidence from $\pm 60^\circ$ (probability 0.5:0.5) after construction of a breakwater offshore of bay of cuspate foreland
Fig. 6 Deformation of sand spits formed under oblique wave incidence from ±60° (probability 0.65:0.35) after construction of breakwater

Fig. 7 Wave field around a breakwater after 5.1 x 10^3 and 5 x 10^3 steps

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rapidly extended to connect the breakwater until $5 \times 10^3$ steps, as shown in Fig. 6(b), and this elongation of the sand spit caused the waves incident from the left to be sheltered in the area right of the breakwater, resulting in the reversal of the direction of longshore sand transport from rightward to leftward. Thus, the direction of the elongation of sand spit B was reversed and extended toward the lee of the breakwater. Sand spit C also rapidly extended rightward because waves incident from the right were sheltered. The construction of the breakwater further affected the beach changes of sand spit D far from the breakwater, and rightward development ceased and a rounded shoreline was formed.

After $1 \times 10^4$ steps, sand spit B rapidly extended to the lee of the breakwater, and after $1.5 \times 10^4$ steps, sand spits B and C markedly elongated to connect to sand spit A, leaving two lagoons behind the breakwater. After $2 \times 10^4$ steps, sand spit B reduced to a tombolo along with the connection of sand spit C with A. After $2.5 \times 10^4$ steps, a double tombolo developed, leaving two lagoons behind. After $3 \times 10^4$ steps, sand was deposited offshore of the breakwater to form a sandy beach, and after $4 \times 10^4$ steps, a new sand spit started to extend from the right end of the breakwater because of the net rightward sand transport.

DISCUSSION

The beach changes observed when a breakwater was constructed, as shown in Fig. 6, can be observed in Taman located in southwestern Russia bounded by the Azov Sea and the Black Sea (Fig. 8). Figure 9 shows an example of sand bars with two lagoons inside in a shallow water body due to the wave-sheltering effect of a shoal (Zenkovich, 1967). Sand bars with two lagoons inside have been formed by the wave-sheltering effect by the shoal shown in the lower part of the figure. The extension of many ridges left of sand bar A shows that waves are incident from the direction normal to shoreline (a). A slender sand bar B also extends with protrusions formed by breaching inside the lagoon on the other side. This indicates that sand bar B was formed by the action of waves incident from the direction normal to shoreline (b). Furthermore, at the tip of sand bar A, a small sand spit C extends rightward. Since the white seabed in Fig. 9 is assumed to show a shallow seabed covered with
sand, a very shallow seabed extends offshore of sand spit C, and on the right side of sand spit C, the seabed depth suddenly increases, implying that sand spit C developed at the corner of the abruptly changed shoreline. This also agrees with the results given by Serizawa et al. (2011). The fact that the tip of sand spit C extended rightward shows the wave action from direction (b). Thus, the sand bars were formed when waves were incident to the coast from two directions in a shallow sea with an offshore shoal. Although the wave-sheltering effect was produced by a shoal in Fig. 9, the same results were obtained in Case 5, as shown in Fig. 6, in which a breakwater was constructed. The calculated results of Case 5 with an offshore breakwater reasonably explained the example of the formation of the sand bars with two lagoons inside and the formation of small sand spit C in Fig. 9.

In Cases 1 and 2, which show the results on a coast with predominant longshore sand transport, a sand spit elongated at the tip of the structure owing to the successive sand supply from the upcoast. This elongation of a sand spit well explains the results observed at Santa Barbara in California (Komar, 1998).

CONCLUSION

On the basis of the study by Serizawa et al. (2012) in which the development of sand spits and cuspate forelands with rhythmic shapes owing to the high-angle wave instability was predicted under natural conditions using the BG model, the impact of anthropogenic factors, such as the construction of a groin or a breakwater, on the beach changes was predicted. It was concluded that the construction of a groin had a considerable impact on the sandy beach, namely, the alteration from the field with the development of the sand spits to that with the elongation of a single sand spit, as well as the acceleration of offshore sand transport because of the blockage of longshore sand transport.

REFERENCES


