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Elongation of a Sand Spit Offshore of Groins Due to High-AnglE Wave Instability

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Abstract

Elongation of a sand spit offshore of groins was investigated using satellite images for the convex shoreline near Cabaruan located on the bottom of Lingayen Gulf in the Philippines. Similar to the extension of a large-size sand spit offshore of Santo Tomas, a sand spit was formed by the longshore sand transport turning around the tip of groins at Cabaruan owing to high-angle wave instability. The elongation of a sand spit was numerically predicted using the BG model (a model for predicting 3-D beach changes based on Bagnold's concept). Predicted results were in good agreement with measured changes in sand spit.

Keywords: Lingayen gulf; High-angle wave instability; Satellite image; Sand spit; Groin; Longshore sand transport

Introduction

On an ordinary coast, the wave angle relative to the direction normal to the shoreline is as small as ±20°. In a bay with a slender shape, however, waves may be obliquely incident to the direction normal to the coastline at a large angle of over 45°. Under this condition, a small shoreline perturbation may develop owing to high-angle wave instability [1]. Lingayen Gulf, located 150 km north of Manila in the Philippines, satisfies this condition, and sand spits have been formed downcoast of the river deltas and on a coast near the bottom of the gulf [2]. This gulf faces the South China Sea, and unidirectional longshore sand transport prevails along the shoreline. Because villages are located along coastlines with such conditions, measures using groins have been taken to protect villages. However, not only the phenomena that are normally observed after the construction of the groins, namely, accretion upcoast and erosion downcoast of the groins, but also the rapid elongation of a sand spit by the longshore sand transport turning around the tip of groins was also observed. In this study, the shoreline changes around the groins constructed in Cabaruan were first investigated using satellite images adopting the convex shoreline located at the bottom of Lingayen Gulf. Then, the elongation of a sand spit by the longshore sand transport turning around the tip of the groins and the formation of a barrier island were predicted using the BG model [3].

General Conditions of Study Area in Lingayen Gulf

Lingayen Gulf is a slender bay of 44 km width and 58 km length with an aspect ratio of 1.3 and faces N20°W, as shown in Figure 1 [2]. The west coast of the gulf is composed of a complicated coastline with many islands and headlands, whereas alluvial fans of the Balili and Aringay Rivers have formed on the east coast of the gulf. Furthermore, a sand spit extends at Santo Tomas 18 km south of the Aringay River mouth.

Lingayen Gulf has a slender shape, and waves incident to this gulf from the South China Sea propagate almost parallel to the direction of the mean coastline, so shoreline undulation may develop owing to high-angle wave instability [2]. To investigate the

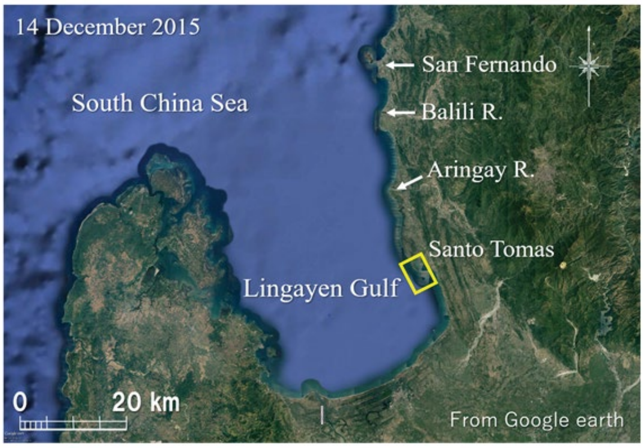

Figure 1: Satellite image of lingayen gulf.

shoreline changes attributable to this mechanism, beach changes in a rectangular area near Santo Tomas, as shown in Figure 1, were studied. Figure 2 shows an enlarged satellite image of this area. West of Santo Tomas, a wetland of 4.5 km length covered by ridges along the coastline extends from Agoo, La Union, and its direction gradually rotates clockwise, while smoothly converging on the present shoreline. This finding explains that sand transported by southward longshore sand transport is being deposited in the lowland, resulting in the gradual shoreline advance.

Topographic Changes around Cabaruan

A rectangular area covering the Cabaruan area shown in Figure 2 was selected as the study area, and the shoreline changes were investigated using the satellite images of the area. First, Figure 3(a) shows a satellite image of Cabaruan taken on 11 November 2016. In this area, the wave angle relative to the direction normal to the shoreline is greater than 45°, satisfying the condition of high-angle wave instability [2]. A sandy beach had continuously extended northwest of groin A, whereas the sandy beach was interrupted at groin A with least sandy beach downcoast of groin A, although wave breaker zone continuously extended in the southeast direction (Figure 3(a)). Then, a sandbar of 540 m length had extended immediately south of groin A by 16 February 2017, while enclosing a slender, triangular lagoon of 324 m length (Figure 3(b)). The sandbar extended from the tip of groin A located at the south end while enclosing a lagoon, and the width of the lagoon decreased southeastward, and disappeared at a location 315 m distant from the groin. These topographic changes clearly indicate that this barrier island was formed by the longshore extension of a sand spit.

Figure 2: Study area of cabaruan near santo tomas on the bottom of lingayen gulf.

Prediction of Elongation of Sand Spit over Groin

Serizawa et al., [4] carried out a numerical simulation of the extension of a sand spit around a groin constructed on a coast satisfying the condition of high-angle wave instability using the BG model. Here, numerical simulation was similarly carried out using the BG model (Type 4) in [3]. First, the wave incidence angle offshore of Cabaruan was assumed to be 55°, taking into account of both the wave angle of 50° estimated from the shape of the wave crest line offshore of Narvacan and the distribution of the wave angle in Lingayen Gulf calculated by the angular spreading method [2]. The initial bathymetry was assumed to be a model topography because of lack of bathymetric survey data in Cabaruan.

During the period between 11 November 2016 and 16 February 2017, a sand spit rapidly elongated owing to longshore sand transport over the tip of the groin, and beach changes in other areas except the sand spit were minimal. Therefore, the model beach with a uniform profile ranging in the depth zone between the berm height *(hR)* and the depth of the closure *(hc)* was set up on the upstream end on a solid bed, as shown in Figure 4, with sand being supplied from the upcoast boundary between *hR* and *hc*, and subsequent beach changes due to wave action were predicted. *hR* is given by 2 m as in [2] and *hc* is approximately

Figure 3: Elongation of a sand spit from around the tip of a groin located at the south end of cabaruan.

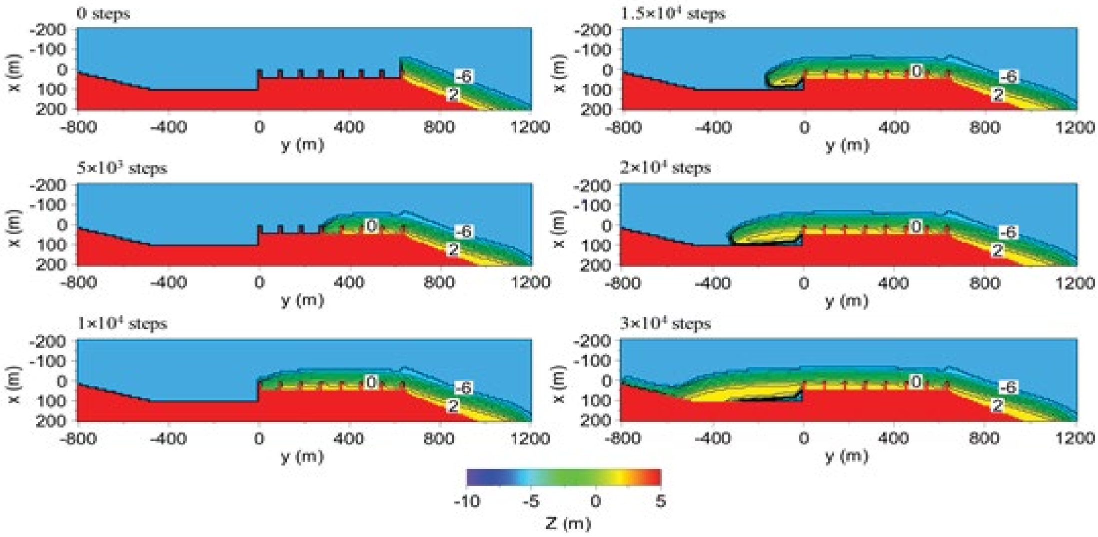

Figure 4: Prediction of development of a sand spit around the tip of groins when waves are obliquely incident to the direction normal to the shoreline at an angle of 55°.

equal to three folds of *hR* as an empirical relationship [2], so it becomes 6 m. Furthermore, a solid flat bed with the depth of *hc* was assumed in the offshore zone. The equilibrium slope was assumed to be the same as the foreshore slope of 1/10 measured on 23 February 2018 at Cabaruan. The initial shape of the coastline was determined from Figure 3(a), and a seawall was set along the coastline concurrently with the installation of eight groins of 490 m length at 90 m intervals. Incident wave height was assumed to be 2 m, which is equal to the berm height, and wave period was assumed to be 8 s. Waves were assumed to be incident from the clockwise direction of θ = 55°. The wave field was calculated using the energy balance equation [2]. The calculation was carried out up to $3×10^4$ steps, where 10^4 steps correspond to 0.9 years. The other calculation conditions are shown in Table 1.

Figure 4 shows the results of the calculation. Because waves are obliquely incident from the clockwise direction at an angle of 55°, leftward longshore sand transport developed, and sand supplied from the northwest (right) boundary was deposited while forming a sand body, which moved southeastward over the tips of the groins. There is a gap between the tip of the groin and the downcoast shoreline at the groin located at the southeast end, so a slender sand spit elongated southeastward (leftward) while leaving a lagoon behind it. Then, a barrier island was formed after the elongation of the slender sand spit. These results and the measured changes shown in Figure 3 are in good agreement. Thus, it is concluded that shoreline perturbation can develop along the shoreline in this area because of high-angle wave instability.

Table 1: Calculation conditions of energy balance equation.

Wave conditions	**Incident waves: $H_{I=}2$ m, T=8 s, wave direction $\theta_{I=}55°$ relative to x-axis**
Berm height	$h_{R=}2$ m
Depth of closure	$h_{c=}6$ m
Equilibrium slope	$\tan\beta_{c=}1/10$
Coefficients of sand transport	Coefficient of longshore sand transport $K_{s=}0.01$
	Coefficient of Ozasa and Brampton term $K_{2=}1.62K_s$
	Coefficient of cross-shore sand transport $K_{n=}K_s$
Mesh size	$\Delta x=\Delta y=10$ m
Time intervals	$\Delta t=0.8$ h
Duration of calculation	$3.2 × 10^4$ h ($4 × 10^4$ steps)
Boundary conditions	Shoreward and landward ends: $q_{x=}0$
	Right and left boundaries: $dq_y/dy= 0$
	Lower right corner of beach edge: $dq_x/dx= 0$ or $dq_y/dy =0$

Conclusions

Offshore of the coast of Santo Tomas located on the bottom of Lingayen Gulf, the wave angle relative to the direction normal to the shoreline was as large as 55°, satisfying high-angle wave instability. On such a coast, many groins have been constructed to protect houses near the coastline against erosion. In the surrounding areas of these groins, the normal condition that the shoreline advances upcoast, and recedes downcoast was observed when the wave incidence angle was small. However, under the high-angle wave instability condition, it was found that longshore sand turned around the tip of the groins, and a slender sand spit rapidly elongated, forming a barrier island with a lagoon inside. This result was explained by a numerical simulation using the BG model under high-angle wave instability. This result clearly indicates that continuous sand supply from upcoast is vital to maintain sandy beach in this area instead of construction of hard structures such as groins.

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