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Sandy Beach Profile Response to Sloping Seawalls: An Experimental Study

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ABSTRACT

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Seawalls are commonly used as a tool for coastal defence worldwide. Most previous studies have considered the case of vertical seawalls and descriptions of existing seawalls, rather than the influence of different designs of sloping seawalls on beach erosion. In this study, laboratory investigations of an undistorted moveable bed model were conducted to determine the resulting beach profile of artificial sandy beaches. In the experiments, three different sloping seawalls were considered under erosive wave conditions with a 50-year return period. The coast of Northern Jiangsu Province, China, is used as a case study. To simulate natural conditions, similarity criteria are developed assuming that the energy dissipation per unit volume along the beach profile is uniform and that the wave properties can be properly scaled by Froude criteria. Field surveys of beach profile changes due to the storm surge induced by Typhoon 9711 were taken to validate the experimental model and good agreements were attained. Spatial profile configurations were studied by examining dominant profile features such as the break point bar and the scour trough on the seawall-backed profiles. Experimental results provided a reference for the maintenance of artificial sandy beaches and the design of seawalls on the coast of Northern Jiangsu Province, China.

ADDITIONAL INDEX WORDS: *Coastal defence, Sandy coast, Sediment transport, Laboratory investigation*

INTRODUCTION

Protection of coastal environments is of vital importance for countries such as China, Australia and Japan, in which the population is concentrated in coastal regions. However, construction of coastal structures alters the hydrodynamic environment when these structures interact with ocean waves. Such interaction will have consequences for sediment transport, and ultimately for beach morphology (KRAUS, 1988; PILKEY and WRIGHT, 1988; BERNABEU *et al.*, 2003). Seawalls are widely used as a tool for coastal defence. Construction of seawalls not only affects the wave field, but also changes the beach profile in front of the seawall, which may cause further beach erosion problems (SILVESTER and HSU, 1993).

In the past few decades, numerous investigations for the wave transformation across the surf zone and its influence on beach erosion have been carried out (e.g. TOLMAN, 1995; LEONT'YEV, 1996; LARSON *et al.*, 1999; GONZALES *et al.*, 1999; TSAI *et al.*, 2001; REGNAULD and LOUBOUTIN, 2002; BERNABEU *et al.*, 2003). On the other hand, the influence of a seawall on the adjacent beach has attracted great attention among coastal engineers. Numerous field and laboratory investigations document the existence of seawall-beach interaction (BARNETT and WANG, 1988; BASCO *et al.*, 1997; KRAUS, 1988). The most often cited effects include changes to offshore profile slope; intensified local scour; adverse down drift erosion; delayed post-storm recovery; and transportation of sand a substantial distance offshore (DEAN, 1986). A detailed literature review of more than 70 laboratory tests, field measurements, theoretical and conceptual studies was reported in KRAUS (1988). However, most previous studies have focussed on wave interaction with vertical seawalls and the description of the existing seawall, rather than the influence of different designs of sloping seawall on beach erosion. Furthermore, current knowledge of the long- and short-term effects of seawalls on beach morphology is limited.

The objective of this study is to determine to what extent sloping seawalls affect artificial sandy beaches on the coast of the Northern Jiangsu Province, China, through a series of laboratory investigations. Based on the experimental results, practical recommendations are made for optimum seawall design.

PHYSICAL MODEL SETUP

Apparatus

Laboratory tests were carried out at the Estuarine and Coastal Engineering Laboratory, Hohai University, Nanjing, China. The tank is 50 m long, 0.5 m wide and 1.2 m high, with sidewalls constructed of glass panels to permit visual observation of profile changes. Wave generation was through a piston-type random wave generator, which was 45m from the toe of the artificial sandy beach model. Data acquisition was accomplished using a capacitance-type wave gauge and a touch-sensitive bottom profiler mounted on a carriage which ran along parallel rails located above the test section. The profiler has ±0.01 m horizontal and vertical accuracies. The data from the wave gauge and the profiler were collected and processed on the computer using the SG600 program.

Scaling Criteria

To ensure laboratory models are representative of prototype conditions, similarity criteria must be established. For adequate similarity between model and prototype, we require that geometry conditions, flow conditions and sediment transport processes are similar. Construction of a moveable bed model requires that horizontal scale, vertical scale, grain size and specific gravity of the bed material are specified. By utilising an undistorted model with sediment identical to the prototype, the transport process can be simulated when the Froude criterion is fulfilled for the flow field, the sediment settling velocity scale ratio behaves as the square root of the length scale, and the sediment is large enough to ensure that a turbulent boundary layer and the properties of a granular material are maintained.

Since beach changes are principally produced in the surf zone, a normal similarity of waves is required in the model in order to satisfy the dynamic similarity of wave action within the surf zone (YEN *et al*., 1988). To simulate natural conditions, similarity criteria were developed on the assumptions that the energy dissipation per unit volume along a beach profile is uniform and that the wave properties can be properly scaled by Froude criteria. Table 1 lists the model scales of different parameters, in which λ_H, λ_L, λ_d, λ_T, λ_u, and λ_ω represent the scale of wave height, wave length, water depth, wave period, water particle velocity, and the settling velocity of sand; while λ_l denotes the horizontal scale.

The sand grain size can be determined by the following formula for settling velocity (YEN *et al*., 1988):

$$\omega = -4\frac{K_2}{K_1}\frac{\upsilon}{D} + \sqrt{\left(4\frac{K_2}{K_1}\frac{\upsilon}{D}\right)^2 + \frac{4}{3K_1}\frac{\gamma_s - \gamma}{\gamma}gD} \qquad (1)$$

where ω is the settling velocity; D is the sand grain size; υ is the kinematic eddy viscosity; γ_s and γ are the volume density of sand and water, respectively; g is the acceleration due to gravity; the coefficients of K_1 and K_2 are equal to 1.22 and 4.27, respectively.

The inception condition of sand movement under wave action should also be similar. Therefore, the determined sand grand size using Eq (1) should satisfy

$$H_* = 0.1\left(\frac{L_0}{D}\right)^{1/3}\left[\frac{L_0 \sinh 2kh}{\pi g}\frac{\rho_s - \rho}{\rho}gD\right] \qquad (2)$$

where H_* is the critical wave height of sand inception; L_0 is the deep water wave length; ρ_s and ρ are the density of sand and water, respectively.

Model Verification

A series of preliminary tests were conducted to verify the incident wave conditions. Wave height records were acquired by sampling with the capacitance gauge immediately seaward of the profile toe.

In each test, the sand beach was moulded to an initial profile with a face slope of 1:8. This profile geometry was determined from the conditions of the artificial sandy beaches on the coast of Northern Jiangsu Province, China. The bed material used in the model tests was a fine quartz sand with a median grain diameter of 0.25 mm, which was determined by sieve analysis of samples with a prototype size of 1.2 mm used to construct artificial sandy beaches in the field. Once the profile had been graded, the tank was filled with water and the sand bed allowed to soak for 24 hours. Before beginning a test, waves were run against the initial profile for one to two minutes to allow for further consolidation of the modelled seabed.

Table 1: Relations and values of different parameters

Parameters	Relation	Value
Wave Height	$\lambda_H = \lambda_l$	20
Wave Length	$\lambda_L = \lambda_l$	20
Water Depth	$\lambda_d = \lambda_l$	20
Wave Period	$\lambda_T = \lambda_l^{1/2}$	4.47
Water Particle Velocity	$\lambda_u = \lambda_l^{1/2}$	4.47
Settling Velocity of Sand	$\lambda_\omega = \lambda_l^{1/2}$	4.47

Field data of beach profile changes due to the storm surge induced by Typhoon 9711 were used to validate the experimental model. The duration of Typhoon 9711 was six hours and the mean wave height and wave period were 2.20m and 7.80s, respectively. The mean water depth was 4.50m. According to the scaling criteria, the wave height was 0.11m, the wave period was 1.74 sec, and the water depth in the tank was 0.225 m. The model verification was run for durations of 3222 seconds.

Figure 1 shows the comparison between the resulting beach profile in the tank and that in the field. An overall agreement between the field measurements and laboratory tests was observed, although some differences at the sand bar existed. This disparity may be explained by the absence of longshore sediment transport under laboratory conditions.

CASE STUDY

With increased development along the coast of Northern Jiangsu Province, China, the utilisation of coastal areas has become imperative and has further augmented the demand for coastal protection. Since the safety and longevity of seawalls is of paramount importance, it is necessary to examine the resulting profile configuration under the erosive wave condition with a 50-year return period.

Three series of tests were conducted in this study. In the tests, regular waves were generated with a height of 0.123 m and period

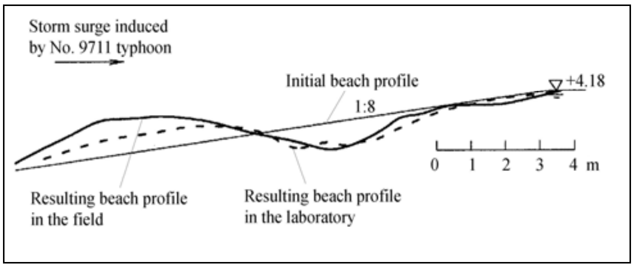

Figure 1. Validation of the moveable bed model through comparison of the beach profile created in the laboratory and that resulting from the storm surge induced by typhoon No 9711

of 1.83 seconds. The water depth in the tank was 0.23 m. These experimental inputs were selected to reflect the in situ conditions of wave height and wave period of 2.46 m and 8.16 seconds with a 50-year return period in a water of depth 4.60 m on the coast of Northern Jiangsu Province, China. These figures were calculated through frequency analysis of the hydrological data at Liangyungang Observation Station.

Each test was run for a duration of 19329 seconds, corresponding to 24 hours' prototype wave action. Profile measurements were then carried out by moving the profiler along three lines parallel to the central line of the tank. The profile configuration was determined by the averaged data of these three measurements.

Three types of sloping seawalls are used in the physical modeling (Figure 2). The conditions of cases are given here:

Case One: The top of the cut-off wall is +4.50m above the Yellow Sea Level; a berm is 4.25 m wide, and the face slope is 1:2.

Case Two: The top of the cut-off wall is also +4.50m above the Yellow Sea Level and the face slope is 1:2; whereas the berm is cancelled.

Case Three: The top of the cut-off wall is up to +5.00m above the Yellow Sea Level and the face slope is 1:3; whereas the berm is also cancelled.

All three of these types of sloping seawalls were constructed with the dry stone pitching.

Figure 2 illustrates the initial profile geometry, the resulting profile configuration with three different types of sloping seawalls. With the exception of local effects due to the presence of the seawall, the main bar-trough features existed for all profiles. However, profile configurations with different kinds of sloping seawalls were remarkably dissimilar. The presence of different seawalls shifted the locations of the break point bar and the scour trough on the resulting profiles.

In Case One, breaking waves rapidly formed a small break point bar formation at a distance of 5.5 m to 6.5 m from the cut-off wall. Experimental results indicate that a beach subject to breaking waves experiences a return flow across the profile that carries sediment stirred up by the wave. LARSON *et al*. (1999) also found that under equilibrium conditions, this transport should take place when no net change occurs in the profile shape, implying that material has to come onshore above the undertow layer to compensate for the offshore transport. Finally, a scour formation 5 m wide and 1.5 m deep was formed at the toe of the cut-off wall, which would destroy the sloping seawall. Moreover, sediment transport seaward of the break point bar was predominantly offshore, forming a small seaward trough, with an offshore bar at the profile toe.

In Case Two, the cut-off wall was moved 4.25 m landward. Due to the artificially increased width from the sloping seawall to the break point, a smaller scour trough of 10m wide, 1.0 m deep at the toe of the cut-off wall was found on the resulting profile. Similarly with Case One, sediment transport seaward of the break point bar was predominantly offshore, forming a seaward trough, with an

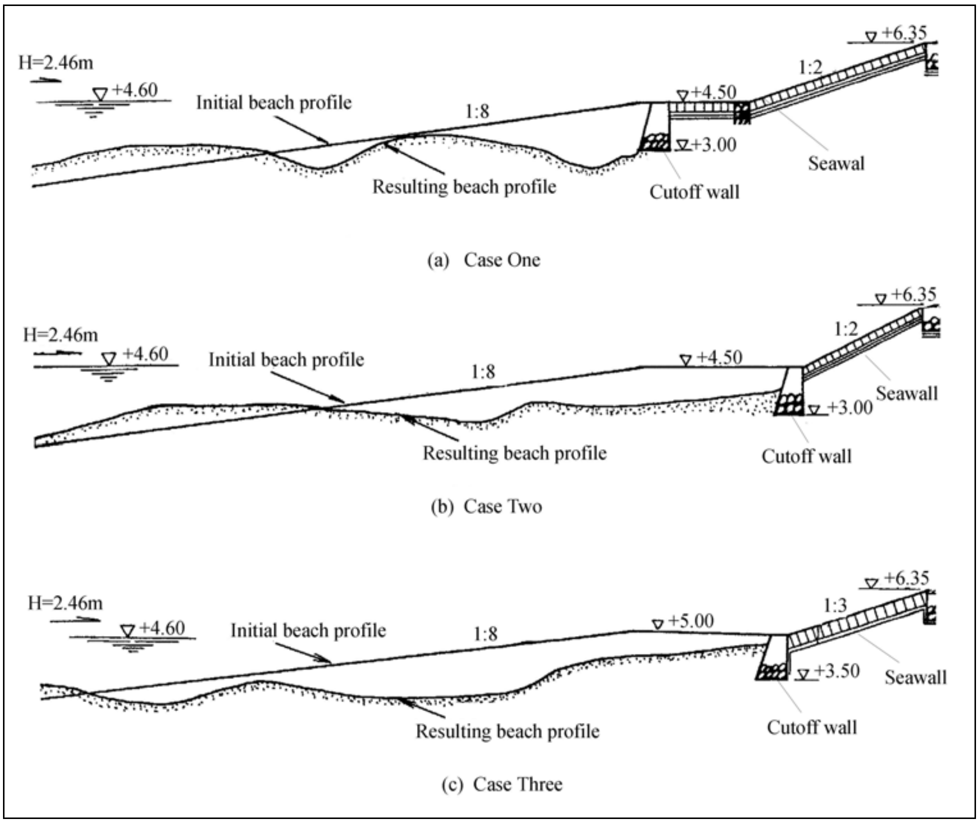

Figure 2. Resulting profile configurations with different kinds of seawalls under erosive wave conditions with a 50-year return period. An initial profile with a face slope of 1:8 was determined by the situation of artificial sandy beaches on the coast of Northern Jiangsu Province, China. Each test was run for a 24 hours prototype wave action.

offshore bar at the profile toe.

In Case Three, the cut-off wall was raised 0.5 m and the face slope of the seawall was flattened to 1:3. Due to the artificially increased width from the sloping seawall to the break point and the decrease of wave reflection, a small scour trough of 12m wide, 0.8 m deep was found on the resulting profile. At the toe of the cut-off wall, the scour trough was only 0.4 m.

By comparing the beach profile configurations corresponding to different kinds of sloping seawalls, and considering that the scour at the toe of seawalls would lead to the damage of coastal structures, Case Three is recommended as the optimum practical design for coastal defence seawalls on the coast of Northern Jiangsu Province, China.

CONCLUDING REMARKS

A two-dimensional undistorted moveable bed physical model with sediment identical to prototype was developed to determine how sloping seawalls affect the artificial sandy beaches on the coast of Northern Jiangsu Province, China. Since beach changes are principally produced in the surf zone, normal similarity of model wave conditions is required in order to satisfy the dynamic similarity of wave action within the surf zone. Field data of beach profile changes due to the storm surge induced by Typhoon 9711 were used to validate the experimental model and good agreements were attained.

Under erosive wave conditions, the dominant spatial feature is a bar-trough system, with the bar forming in close proximity to the point of wave breaking and the trough occurring near the still water shoreline. Wave breaking and wave reflection appear to play a significant role in the formation of a scour trough in front of a sloping seawall. In order to reduce erosion at the toe of the seawalls and avoid damage of coastal structures under extreme sea states, the sloping seawall should be constructed far from the surf zone and the face slope should be decreased. On the basis of the laboratory investigations, Case Three is recommended as the most appropriate design for coastal seawalls on the coast of Northern Jiangsu Province, China.

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