MORPHODYNAMICS OF INTERTIDAL SAND BARS: FEEDBACK BETWEEN SEDIMENT TRANSPORT AND SUCTION DYNAMICS EFFECTS

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Intertidal sand bars experience a full spectrum of wave and current processes, yet appear at about the same locations every time they become exposed during low tides. This persistent nature has been the subject of much speculation concerning the hydrodynamic mechanisms involved, but its origin remains an enigma. In the present study, we aim to resolve this question by introducing salient physics to the analysis of intertidal sediments, in contrast to the physics of fluids above the sediments. Our recent finding shows that the dynamics of suction, i.e., negative pore water pressure relative to atmospheric air pressure, brings about a significant elastoplastic contraction in the cyclically exposed and submerged sediments, depending strongly on the intensity of the prevailing suction dynamics, thereby giving rise to distinct variations of the surface shear strengths of the sediments. The physical evidence, combined with theoretical modeling and analysis in the context of morphodynamics, demonstrates that such geodynamic processes ensuing during exposure periods have a profound impact, yielding the persistent nature of the intertidal bars during submergence periods under severe hydrodynamic forcing which would otherwise lead to unstable bar behaviour. Notably, the feedback between the effects of the suction dynamics and sediment transport and morphology is found to play a crucial role in the intertidal bar morphodynamics. Hence, our finding may fundamentally alter the current perspective, leading to a new level of understanding, of sediment transport and bar behaviour at waterfronts that are ubiquitous in rivers, estuaries, and coastal seas.

Key Words : *Intertidal Sand Bars, Morphodynamics, Sediment Transport, Shear Strength, Suction Dynamics*

1. INTRODUCTION

Sand bars are common morphological features in rivers, estuaries, and coastal seas. In the marine environment, they are situated in subtidal and/or intertidal zones. Sand bars play an important role in beach stability since they reduce the energy of waves by breaking them, thereby preventing severe erosion. The hydrodynamics and associated sediment transport processes involved have thus been extensively investigated to understand the sand bar morphodynamics[1),2),3)]. Sand bars typically move offshore during storms and move back onshore to form a berm under calm wave conditions. However, there are persistent intertidal sand bars that are subdued and static even in the presence of sufficiently strong waves, but their origin remains an "enigma"[2)].

In the present study, we aim to unravel the origin of such persistent sand bars. To this end, we introduce our recent findings on the salient physics involved in intertidal sediments, which contrasts sharply with the physics of fluids above the sediments. We have previously demonstrated that the dynamics of suction, that is, negative pore water pressure relative to atmospheric air pressure, play a substantial role in the temporal and spatial evolution of voids and surface shear strength in cyclically exposed and submerged sediment [4]. In this paper, we explore the role of such geodynamic processes in the intertidal bar morphodynamics.

The organization of this paper is as follows. We first review the intertidal bar morphology in relation to the prevailing hydrodynamic and sediment transport characteristics. We then present physical evidence concerning the effects of the suction dynamics, followed by a description of their modelling and analysis in the context of sediment transport and bar morphology.

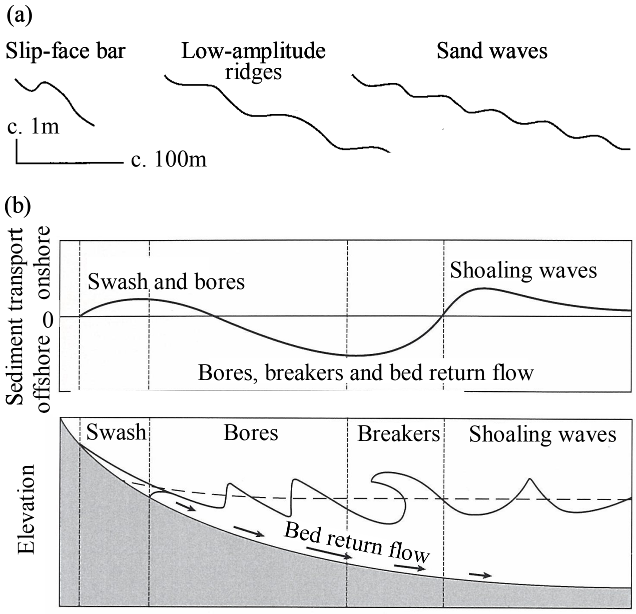

Fig. 1 (a) Three main intertidal bar types; (b) sediment transport rate and direction associated with dominant hydrodynamic processes (adapted from Masselink et al.[2])

2. INTERTIDAL SAND BARS: THEIR PERSISTENCE IN THE PRESENCE OF WAVES AND CURRENTS

Intertidal sand bars can generally be categorized into three main types depending on their amplitudes and slopes: slip-face bars, low-amplitude ridges, and sand waves (Fig. 1a). Slip-face bars present the most pronounced and dynamic morphology. They migrate offshore during storms and remigrate onshore under prolonged calm wave conditions, a characteristic common to subtidal bars. By contrast, the low-amplitude ridges, and especially the sand waves, are fairly static. Despite the presence of much speculation concerning the hydrodynamic characteristics, their origin remains unclear [2].
The submerged intertidal bars experience a series of wave processes, including shoaling, wave breaking, swash and return flow, in the course of water level changes during tides (Fig. 1b). Accordingly, the associated cross-shore sediment transport is unsteady in space and time, with its direction cyclically changing between offshore and onshore (Fig. 1b).

In what follows, we consider two representative examples showing the morphodynamic stability of intertidal multiple sand bars. Fig. 2a shows the results of field surveys performed during a 7-year period from 1994 to 2000 on the Banzu intertidal flat located on the east coast of Tokyo Bay, Japan [5]. The soils were fine-grained sands with D_{50} in the range of 0.17 to 0.23 mm. Multiple sand bars were present on the lower intertidal zone, with heights of 0.1 to 0.2 m and lengths of 40 m on a gentle slope of 1/1000. There were temporal variations in the average ground heights due primarily to the net deposition with an average rate of 0.04 m/year [6]. However, except for the one at the offshore front, the bar locations remained stationary.

Fig. 2b shows the results of 26 field surveys performed during a 3-year period from 2003 to 2005 on Okoshiki beach located in Ariake Bay, Japan [7]. The soils were fine-grained sands with D_{50} in the range of 0.12 to 0.33 mm. Multiple sand bars with heights of 0.15 to 0.5 m and lengths of 30 to 50 m were present on a mild slope of 1/300. Except for the offshore fronts, the bar locations remained essentially the same.

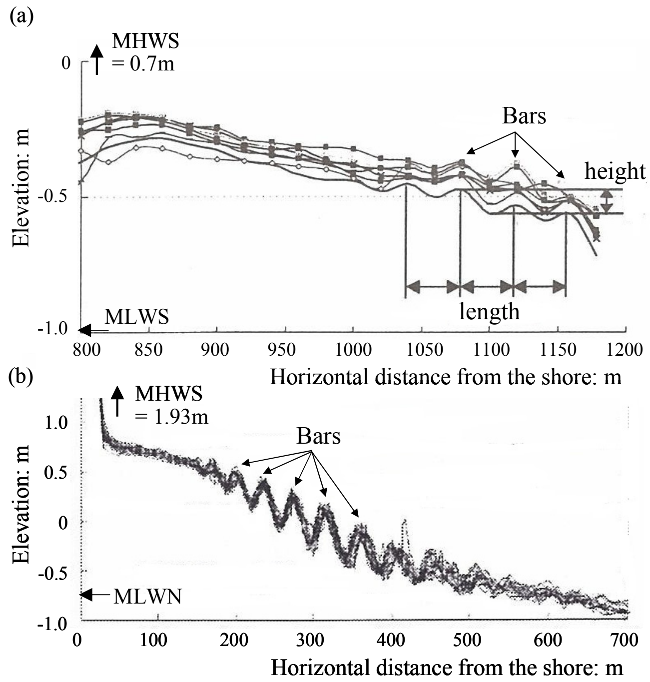

Fig. 2 Results of field surveys showing the morphodynamic stability of intertidal sand bars at (a) Banzu sandy flat [5] and (b) Okoshiki beach [7].

During the periods of both surveys, the two different sites experienced occasional seasonal events such as storms and typhoons [5),7)]. This fact, together with the above field results, indicates the persistent nature of the intertidal sand bars in the presence of waves and currents.

3. SUCTION DYNAMICS AND ITS EFFECTS ON SEDIMENT TRANSPORT AND MORPHOLOGY

(1) Physical Evidence

Sediments in intertidal zones are cyclically exposed and submerged. Thus, there are temporal changes in the groundwater level, causing dynamic changes in the suction state of the sediments [4]. Suction represents the tension of moisture in the sediment and is defined by

$$s = u_a - u_w \tag{1}$$

where u_a is the atmospheric air pressure and u_w is the pore water pressure in the sediment. By definition, suction is equal to zero at the groundwater level.

Through a combination of field, experimental, and theoretical investigations, we have revealed the following [4]. The dynamics of suction in association with tide-induced groundwater level fluctuations bring about a significant cyclic elastoplastic contraction in repeatedly exposed, yet saturated sediments. Such suction-induced void state changes give rise to distinct variations in the surface shear strengths of the sediments, the magnitudes of which depend strongly on the intensity of the suction dynamics ensuing there.

For the purpose of illustration, we describe the results from our field observations, as typified by Fig. 3. While the sediment grain sizes were essentially similar, at $D_{50} \cong 0.2$ mm, the groundwater level varied markedly with the bar-trough morphology in the lower intertidal zone. This variation was directly reflected in the development of suction, under conditions where the sediments remained saturated during the periods of exposure. In the course of the tidal cycles, the bars experienced larger groundwater level variations, thereby undergoing stronger suction dynamics. As a result, the bars became denser and developed significantly higher surface shear strengths than the troughs.

Overall, these effects of the suction dynamics yield a close relationship between the distributions of the surface shear strengths and the variations of the morphological heights in the lower intertidal sediments.

(2) Modeling and Analysis

Sediment becomes mobile when the surface shear stress exerted due to waves and currents exceeds a threshold shear stress of the sediment. Under severer conditions, the thickness of the mobile layer increases with increasing sediment transport rate, which is constrained by a unique relationship at the

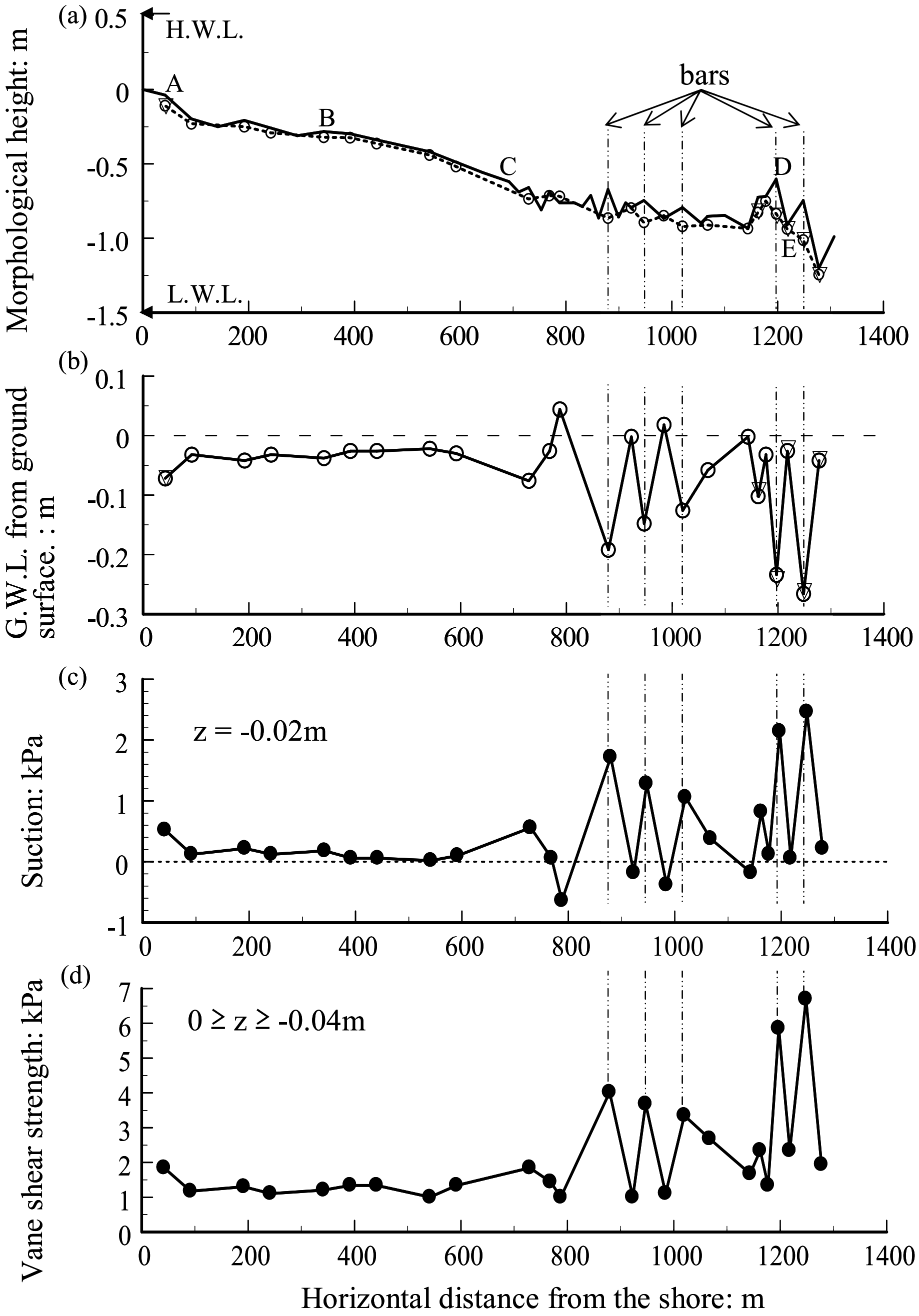

Fig. 3 Results of field observations and surveys showing a close relationship between the variations in surface shear strengths and bar-trough morphology in the lower intertidal zone. The points marked A to E represent the locations of sediment sampling in Sassa and Watabe [4].

bottom of the mobile layer, namely, that the shear stress must be equal to the shear strength there (Fig. 4). This shows that the sediment transport rate is a function of both the shear stress and shear strength of the sediment. Although significant advances have been made in understanding the evolutions of the shear stresses, current approaches to sediment transport modelling explicitly assume the shear strengths to be fixed in the sediments [1),2),3),8)]. The former section of this paper, however, has clearly shown that the intertidal sediments exhibit distinct variations of the surface shear strengths due to the effects of the suction dynamics.

Below, we will describe a simple, yet physically based model for the effects of the suction dynamics on sediment transport and morphology.

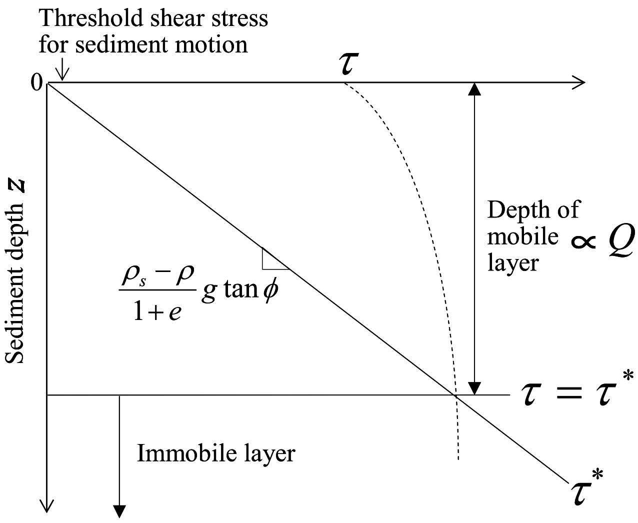

Fig. 4 Sketch showing sediment transport rate Q as functions of both shear stress τ and shear strength τ^* of sediment. Here g is earth's gravity, ρ is mass density of fluid, ρ_s is mass density of sediment particles, e is void ratio of sediment and ϕ is internal friction angle of sediment.

The equation of continuity for sediment mass in a cross-shore direction x can be expressed by

$$\frac{\partial z}{\partial t} = -\frac{1}{1-n}\frac{\partial Q}{\partial x} \tag{2}$$

where z is the ground height, n is the porosity of sediment, and Q is the cross-shore sediment transport rate. The sediment transport direction is cyclic in space and time due to the intertidal hydrodynamic characteristics. Thus, Q may take its simplest form

$$Q = A \cdot \sin(\kappa x - \omega t) \tag{3}$$

where $\kappa = 2\pi / L$ and $\omega = 2\pi / T$ are the wave number and angular wave frequency of Q, respectively, and A represents the maximum sediment transport rate, which depends on both the given shear stress and the shear strength in the sediment. Consideration of the close relationship between the effects of the suction dynamics on the shear strength and the morphological height distributions yields

$$A = a|z| \tag{4}$$

where a is a parameter that is constrained by the given shear stress on the sediment.

Analysis of the intertidal bar morphodynamics was performed on the basis of eqs. (2) to (4). With a given initial geometry and wave and sediment conditions, eq. (2), incorporating eqs. (3) and (4), was solved using an implicit finite difference method. The ground height distributions obtained were used to update eqs. (2) to (4). Calculations continued for a target number of time steps. The initial bar geometry was set as: length 40 m, height 0.25 m, slope 1/500. The parameters used were: T = 1 year, L = 40 m, n = 0.45, a = 0.0075 m^2/day. Analysis in the absence of the effects of the suction dynamics was also performed by setting $A = a$ in eq. (4) for the purpose of comparison.

(3) Results and Discussion

The sand bar behaviours with and without the effects of suction dynamics are plotted in Fig. 5. In

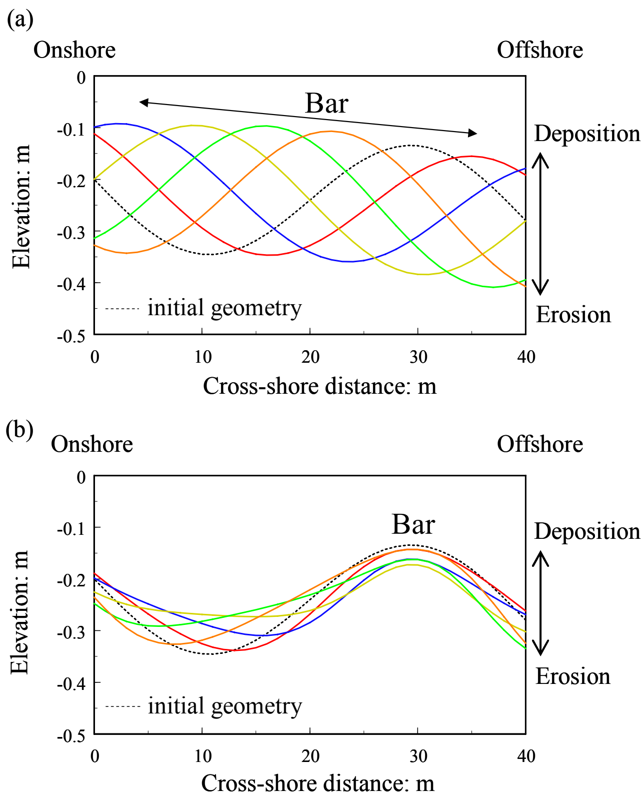

Fig. 5 Results of analysis (a) without and (b) with the effects of suction dynamics

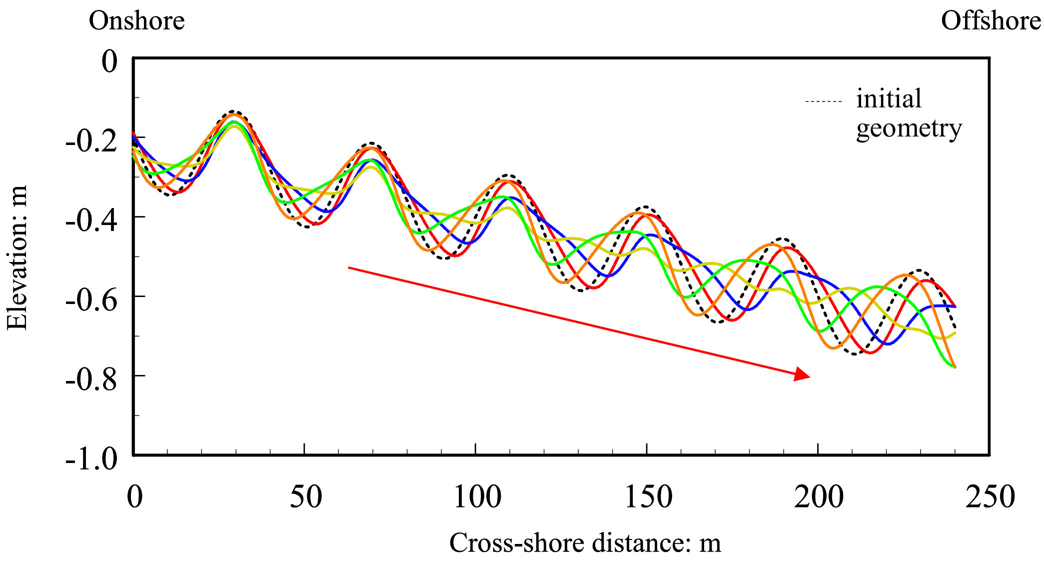

Fig. 6 Results of analysis showing the transformation of bar behaviour in the offshore direction

the absence of the geodynamic effects, in other words, solely under the influence of hydrodynamic agents, the sand bar undergoes periodic offshore and onshore movements. Indeed, while the bar heights remain essentially constant, dynamic morphological changes ensue due to the repeated erosion and deposition. By contrast, the geodynamic effects alter the bar behaviour sharply. The morphological changes become markedly suppressed in such a manner that the bar heights vary but their locations remain the same, indicating the persistent nature of the sand bars.

The results demonstrate that a simple yet realistic consideration of the effects of suction dynamics can account for the persistence of the intertidal sand bars subjected to a severe hydrodynamic forcing which would otherwise lead to unstable bar behavior. It is important, however, to remark that the way in which the geodynamic effects manifest themselves can vary depending on a number of factors, including bar morphology, slope, location in the cross-shore direction, and sediment grain size. One such example is illustrated in Fig. 6, showing that the bar behaviour becomes gradually dynamic in the offshore direction, due to the decreasing effects of the suction dynamics. Indeed, one can observe the sequence of processes of bar generation, migration, and development and decay at the offshore fronts. Also, under conditions where the sediment becomes unsaturated stemming from the coarse grain size or enhanced bar height, for example, in the case of slip face bars, the effects of suction dynamics may become less pronounced, allowing dynamic bar movement.

The above discussion emphasizes the importance of properly considering the interplay between the prevailing hydrodynamics and the geodynamic effects in the intertidal bar morphodynamics.

4. CONCLUSIONS

Recent findings about the salient physics involved in intertidal sediments have led to a substantial new insight into the intertidal bar morphodynamics. Namely, the morphodynamic stability of the intertidal sand bars, which has thus far remained elusive, has been found to manifest itself due to the interplay between the effects of the suction dynamics and sediment transport and morphology. The present finding is relevant to sediment bars which experience periodic exposure events that occur in rivers, estuaries, and coastal seas. Thus, it can effectively contribute to the engineering design and maintenance of such morphological features, which are often crucial for disaster reduction as well as for conservation and restoration of habitats with diverse ecological activity.

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