

Experimental Study on Distinctive Small-Scale Seabed Forms in Coastal Zone

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(沿岸域における特徴的な微小海底地形に関する実験的研究)

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論文内容の要旨

Thesis Summary

In the coastal zone, seabed sediment such as sand is transported by hydrodynamic mechanisms. This phenomenon is known as the sediment transport, which is classified as suspended load or bed load. Quantitatively elucidating the hydrodynamic mechanism governing the sediment transport is essential for predicting the coastal morphological changes such as coastal erosion, and represents a fundamental research challenge in the fields of coastal engineering and geomorphology.

When oscillatory flows impact on the seabed as dynamical forcing, a variety of small-scale seabed forms emerge through the interaction between the flow structure and the sediment transport. Among them, sand ripples have garnered significant attention due to their geometric regularity and influence on the sediment transport through suspended load. While the most commonly observed ripples in the ripple morphology are two-dimensional, the formation of three-dimensional structures known as brick-pattern ripples occurs under specific hydrodynamic and bed material conditions. Such a pattern, characterized by longitudinal bridges alternately lined between the ripple crests perpendicular to oscillatory flow direction, resembles a "brick-pattern". Clarification for the hydrodynamic transition from two-dimensional to three-dimensional ripples under oscillatory flow becomes a significant challenge in geomorphology, with limited experimental studies addressing the precise formation conditions and parameters governing the brick-pattern ripple formation.

On a sloping sandy bed in the nearshore zone, we often observe breaking waves generated under a critical condition. The subsequent swash and backwash flows impose periodic and unsteady hydrodynamic forces on the seabed. The mass transport in the onshore direction driven by progressive waves is counterbalanced by the offshore return flow near the bottom. The interactions between breaking waves, wave-induced flow and bedform generate vortex structures and vertical circulatory flows in the nearshore zone, and they contribute to the formation of distinctive seabed forms such as sandbar. Previous experimental studies have suggested that the flow structures around the wave-breaking point become a key mechanism influencing the generation of sandbar. However, the detailed characterization of the flow structures and their contributions to the sediment transport and bedform evolution still remain poorly clarified.

This study aims to experimentally investigate the formation conditions and mechanisms governing distinctive small-scale seabed forms in the coastal zone, providing critical insights into the interaction between hydrodynamic forcing and sediment transport process. Two specific seabed structures are targeted: (1) brick-pattern ripples, which have been subject to limited experimental scrutiny, and (2) flow structures associated with breaking waves and sandbar. The outline of this thesis and findings in the respective chapters are as follows:

We described the background and the objectives of this study in Chapter 1. By reviewed theoretical and experimental findings in previous studies, the ideas and associated research topics in this study were summarized. The outline of the thesis was also listed in this chapter.

In Chapter 2, the geometric properties and the formation conditions of brick-pattern ripples were systematically examined through a series of controlled laboratory experiments under various oscillatory flow conditions. By utilizing a U-shaped oscillatory flow water tank and introducing glass beads instead of natural sand, laboratory experiments were conducted on the basis of a wide range of dimensionless parameters to establish the formation regimes. The

experimental results indicated that the crest wavelengths of brick-pattern ripples are slightly smaller than the oscillation stroke. The critical value of the flow Reynolds number at the transition to brick-pattern ripples, defined with respect to the Stokes layer thickness, was found to be around 65 when the sediment Reynolds numbers based on the sediment diameter ranges from 30 to 50. Employing dimensionless parameters such as the Taylor number and oscillatory flow amplitude ratio, we estimated the critical Taylor number of $T_a=1.74$, whose value is suitable in comparison with the experimental results. This fact supports that the centrifugal instability is important in the brick-pattern ripple formation.

Chapter 3 provided the Structure-from-Motion (SfM) photogrammetry to construct three-dimensional digital elevation models of brick-pattern ripples. By ensemble averaging the spatial elevation data, a unit model representing the periodic geometry of brick-pattern ripples was generated for both oscillatory and transverse directions, assuming symmetry was preserved. The SfM analysis confirmed quantitatively that the bridge wavelengths exceed those of the ripple crests, while the bridge heights are relatively lower than those of the ripple crests. These findings provide novel insights into the morphodynamical processes underlying the three-dimensionality of brick-pattern ripples.

Chapter 4 investigated the flow structures around sandbar by using a particle image velocimetry, i.e., PIV. The flow velocity fields generated by wave-induced flow in the cases of the plunging breaker and surging breaker were measured in a small wave tank with sloping bed. The boundary layer separation around the wave-breaking point was observed on the sloping bed under the condition of the plunging breaker. The experiments utilizing a triangle sandbar model attached on the sloping bed demonstrated the vortex structures generated due to the plunging breaker. Though these experiments could not reproduce full-scale phenomena, they suggested characteristics of the vortex structures around sandbar during the wave-breaking events. The time-averaged flow structures also indicated that certain wave conditions favor the development of vertical circulatory flows, which may contribute to sandbar growth.

In Chapter 5, we stated the conclusions of this study with a comprehensive summary of experimental results and findings. This research advances the understanding of the formation mechanisms of brick-pattern ripples and sandbar, relating to the bedform evolution in the coastal zone. The new findings in this study provide valuable insights into the sediment transport dynamics, with significant implications for both of theoretical research in coastal geomorphology and practical application in the field of coastal engineering.