Dune dynamics in coarse silt, sand and gravel along the main channel from the estuarine front of the Yangtze River to the Three Gorges Dam.

Heqin Cheng *State Key Laboratory of Estuarine and Coastal Research, East China Normal University – hqch@sklec.ecnu.edu.cn*
Lizhi Teng *State Key Laboratory of Estuarine and Coastal Research, East China Normal University*
Wei Chen *Helmholtz-Zentrum Geesthacht, Max-Planck-Straße 1, 21502 Geesthacht, Germany, wei.chen@hzg.de*

ABSTRACT: Most past studies of dune dynamics have concentrated on dunes in a spatially-homogeneous natural environment. This environmental simplification imposed inherent limitations on understanding of dune form, flow and sediment dynamics in channels affected by human interventions. This paper details a field study of a swath of dunes in a set of particle sizes as coarse silt, sand and gravel in the main channel from the downstream of Three Gorges Dam (TGD) to the estuarine front of Yangtze River (YR), China for recent 22 years. Results show four new types of dune changing in spatial and temporal distribution. They reveal a complicated pattern of dune morphology and associated flow structure mainly attributed to the dam and channel changes by land reclamation. Froude number was applied into the bedform pattern recognition in the low flow velocity regime along the lower reach of the YR and higher accuracy of recognition was achieved.

1 INTRODUCTION

Dunes are ubiquitous bedforms in marine and riverine environments and occur in a wide range of bed sediment particle sizes. Numerous studies in natural environments in unidirectional flow (river) and reversing flow (estuaries and other tidal environments) and in controlled settings (flumes) have demonstrated that bedform size is generally related to sediment size: larger dunes form in coarser sediment (Ashley, 1990; Van den Berg and Van Gelder, 1993; Baas, 1994; Best, 2005; Parsons et al., 2005; Malarkey et al., 2015; Hu et al., 2018).

However, most of these dune dynamics studies have concentrated on dunes in a spatially-homogenous natural environment and in the flume (McLean et al., 1994; Kostaschuk and Best, 2005; Lefebvre et al., 2013). This environmental simplification imposed inherent limitations on the interpretation and understanding of dune form, flow and sediment dynamics in channels affected or controlled by strong human interventions. Examples of anthropologically-modified environments include the main channel downstream of the Three Gorges Dam, Yangtze River (YR) where a strong erosion takes place (Zheng et al., 2018) combined with climate change and sea level rise (Cheng et al., 2018; Shi et al., 2018).

This paper details a field study of dune morphology in a set of particle sizes ranging from coarse silt to sand and gravel in the main channel from downstream of the Three Gorges Dam to the estuarine front of the YR, China. The aim of this work was to characterise flow pattern and bed morphology over a wide range of sedimentological and hydrological conditions.

2 STUDY AREA AND METHODS

The Yangtze River (Figure 1) is the longest river in China. It has been strongly affected by anthropogenic works such as the Three Gorges Dam and land reclamation along the main channels for more than 20 years (Zheng et al., 2018; Cheng et al., 2018). Nine survey cruises during May 2014 and September 2017 were conducted with a total length of survey of over 5000 km along the channel from downstream of the Three Gorges Dam to the estuarine front of the YR using a SeaBat 7125 multi-beam echo sounder (MBES). Simultaneously to the MBES survey, flow information was measured using an Acoustic Doppler Current Profiler (ADCP).

Field studies were carried out in order to further improve our understanding of the fundamental sedimentation and morphodynamic processes acting on subaqueous bedforms during the 1997, 1999, 2000, 2002, 2014, 2015 dry season and the 1998, 2013, 2014, 2015, 2016, 2017 flood season in the uppermost estuarine turbidity maxima. Water depth and near surface tidal current speed/direction were measured at 3- minute intervals for 14 hours in 1997 and 26 hours in all other surveyed duration, while near-bottom tidal current speed and direction were measured at 30-minute intervals for 10 hours in 1997 and for 1 minutes in all other surveyed duration. A total of 1648 water samples were collected at 0.6Z, 0.8Z, and 1.0Z (Z being the total water depth), from which the suspended sediment concentration was analysed. Vertical profiles of the suspended sediment concentration were also measured by using an Acoustic Suspended Sediment Monitor. The transverse profiles over the low angle subaqueous bedforms were recorded in the along channel direction. A total of 16 bed sediment samples were grabbed and analysed for their particle size.

3 RESULTS

The surveys revealed a complicated pattern of dune morphology and associated flow structure. Four new types of erosive subaqueous dune are discovered and new transition function of bedform for the recognition.

(1) Low angle dunes in coarse silt and very fine sand in the estuarine front of the YR and their seaward migration

Analysis results show a tidal asymmetry, i.e., longer period and stronger current speed in ebb than in flood, resulting in a higher suspended sediment concentration during the ebb due to the tidal resuspension of the bed sediment, thus causes a transport of the suspended sediment seaward in the estuarine turbidity maxima (Cheng et al., 2000). It is suggested that resuspension might be a dominant sediment process on the subaqueous bedforms in coarse silt and very fine sand. Ripples and dunes result from the strong resuspension of bed sediments compose of a wide range distribution of particle sizes. Ripples and small scale dunes might be formed in response to long-period resuspension events instead of short-period, burst-like boils over dune crests. Medium scale dunes occurred in a 2-4 minute period of the enhanced bottom sediment suspension. A new conceptual model is proposed for the sediment and morphodynamic processes on the subaqueous bedforms in coarse silt and very fine sand in a semi-diurnal tidal estuary (Cheng et al., 2000).

Moreover, the sets of field-measured records in the main channels of upper estuarine turbidity maxima show that the distributed front of dune in fine sediment migrated seaward for the past 20 years (Li et al., 2008).

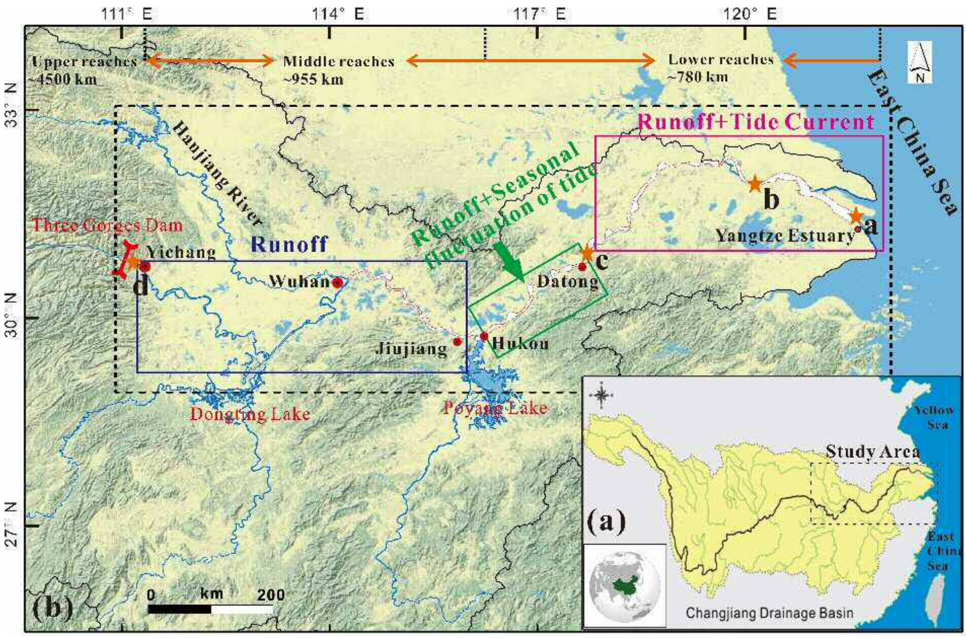

Figure 1 Study area of the dune dynamics along the Yangtze River from the downstream of the Three Gorge Dam to the estuarine front of the Yangtze River. In plot (b), a, b, c, d are the survey locations of subaqueous dune.

(2) Erosive dunes in very fine sand on the eroded riverbed of channel in lower Yangtze estuary

A new type of dune was defined as a catenary-bead dune, which consists of a catenary dune and its associated elliptical pit (Zheng et al., 2016a). It has a mean height and wavelength of 1.29 m and 31.89 m, respectively; wavelength/height ratio (L/H) of 14 to 56; and elliptical pits of mean and maximum depth 0.98 m and 1.98 m, respectively (Figure 2a). Mean flood and ebb velocities over the dunes are 0.27 and 0.78 m s^{-1}, respectively, with shorter duration of flood tide. The silt, very fine sand, and fine sand fractions were within the ranges 21.6–23.4%, 28.2–32.2%, and 39.7–41.6%, respectively, revealing complex bed material composition. Water depth varies from 13 to 17 m.

(3) Very large dunes (VLDs) in fine and medium sand in the upper Yangtze estuary and VLDs accompanied by secondary dunes in the middle reach of the YR

In the upper estuary and middle reach of the YR, two types of very large dunes were detected in unidirectional flow according to their morphological characteristics (Zheng et al., 2016b). The mean grain size of the riverbed surface sediments is between 0.137 mm and 0.262 mm, named as fine and medium sand.

The first type is the VLDs with a smooth surface and cross-section on the silted riverbed of channel in the upper estuary (Figures 1 and 2b). The average dune spacing is 122.8 m and their mean height is 3.9 m with a mean L/H of 35.4. Water depth ranged from 13.4 m to 17.6 m and simultaneous vertical average flow velocity changed from 0.78 to 0.99 m s^{-1}.

The second type is the VLDs accompanied by secondary dunes and numerous elliptical pits on the eroded riverbed of channel in the upper estuary (Figures 1 and 2c).

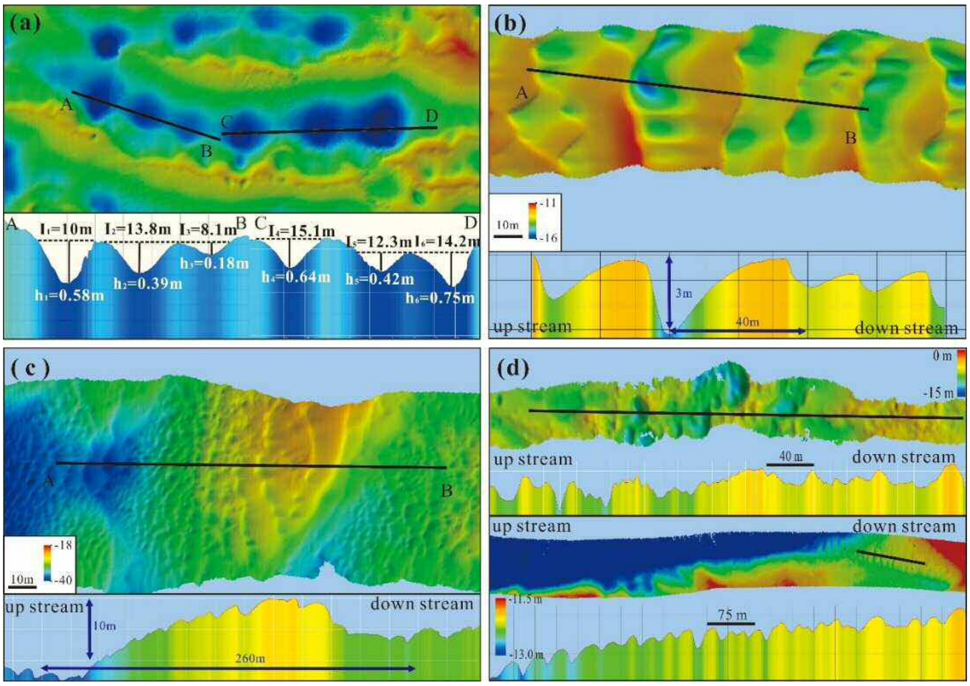

Figure 2. The multi-beam mapping for characteristics of subaqueous dunes along the main channel in the middle and lower reaches of the Yangtze River. (a) Maps of typical characteristics of catenary-bead dunes in very fine sand showing inlaid elliptical pits; (b) Maps of morphology of a very large dune in fine sand with a smooth surface in the silted channel; (c) Maps of morphology of a very large dune in fine sand with a smooth surface imposed on the catenary-bead dunes in the eroded channel; (d) Maps of very large dune in gravel along the channel from downstream the Three Gorge Dam to Yichang.

The mean spacing of dunes changed from 184.5 m to 204.3 m and mean height varied from 4.1 m to 4.3 m with a mean H/L of 55. 1 to 56.3. The water depth varied from 17.6 m to 29.9 m and simultaneous vertical average flow velocity ranged from 0.96 to 1.22 m s^{-1}

(4) Very large dunes (VLDs) in sandy gravel with strong unidirectional flow along strong eroded channel downstream the Three Gorge Dam (TGD) to Yichang

An area covered with dunes was surveyed downstream of the Three Gorge Dam. The dunes showed a mean spacing of 89 m ranging from 40 m to 267 m and a mean height of 5 m ranging from 5 m to 13 m. Secondary erosive catenary–bead dunes were also imposed on the lee and stoss slope of dunes in gravel (Figure 2d). The mean particle size is 7.90 mm and medium particle size is 10.52 mm. The sorting coefficient is 12.52. Their scales are larger than most of dunes in gravel studied for the bed load estimation and criteria of flow in the flume experiments and few subaqueous dunes in gravel detected in, e.g., the Severn Estuary (Carling et al., 2006) and the continental shelves in Italy (Iacono and Guillén, 2008).

(5) Application of Froude number in the pattern recognition of bedform in low flow velocity regime along the lower reach of the YR

Specific concern is given to the effects of Froude number on the pattern recognition of bedform in low velocity regime. A three-dimensional (3D) phase diagram of dune stability for the recognition is proposed, in Froude number (Fr), Reynolds number (Re_*) and Shields number (Θ) of sediment grains (Figure 3). These parameters are calculated from flow velocity obtained with ADCP, morphological parameters of bedforms detected by MBES, sediment and particle size, simultaneous real-time water level in typical channels in tidal reach of the YR. The results show an increasing accuracy of bedform pattern recognition with three parameters of Froude number, Reynolds number and Shields number by 35% than two parameters Reynolds number and Shields number. This 3D diagram can also increase the recognition accuracy of bedform by 30% than those with two parameters of dimensionless Shields number and Reynolds number Re*. The deviation of dune recognition without Fr ranged from 40% to 80%.

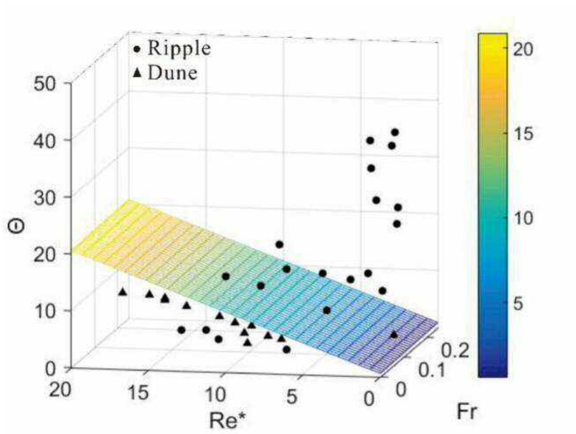

Figure 3. Map showing the stability diagram of dunes with Froude number (Fr), Reynolds number (Re*) and Shields number (Θ).

4 CONCLUSIONS

Changes in morphology, flow and sediment dynamics over a main channel ca. 1600 km were examined from the estuarine front of the YR to downstream of TGD, China. The dunes composed of coarse silt, very fine sand, fine sand, medium sand and sandy gravel displayed a complicated pattern of dune morphology and associated flow structure. Four new types of dunes with spatial and temporal changes were discovered with emphasis on the findings of erosive dunes which imply strong effects of the Three Gorges Dam and changes in channel morphology by land reclamation and sand mining, dredging. Application of Froude number into the bedform pattern recognition in the low flow velocity regime can increase the accuracy of bedform recognition. These findings enrich the description and understanding of dune dynamics and provide important data for geomorphological research.

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