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Morphodynamic responses of Caofeidian channel-shoal system to sequential large-scale land reclamation

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ABSTRACT

Understanding the influence of reclamation projects on a channel-shoal system is of vital importance regarding the management and sustainable development of coastal regions. This study addresses the issue by applying a processes-based morphological model to investigate hydro-morphodynamics of Caofeidian channel-shoal in five phases of large-scale reclamation project from year 2003 to 2020. Forced by the spring-neap tidal cycles and representative waves, the model considers multi-fraction sediment dynamics regarding strong spatial variations of mud-sand mixtures in the study area. The numerical results demonstrate that sequential large-scale land reclamation induces continuous loss of sediment volume of tidal flat by reducing its sediment storage capability. The morphodynamics of channels is complex in space and perturbation of reclamation location increases this complexity. For the channels in the western uninterrupted coast, reclamation affects their morphological evolution by damping the long-shore sediment transport. The tidal asymmetry is a key factor in the geomorphology of channels in the eastern inlet-interrupted coast (Laolonggou lagoon-inlet system), which is impacted by the reclamation location. Particularly, reclamation constricting the inlet dampens the flood tidal asymmetry and triggers the deepening of inlet, while tidal flats reclamation in lagoon enhances flood tidal asymmetry which induces the siltation of inlet. The model also reveals different behaviors of multi-fraction sediments, of which the silt with larger settling velocity is subject to the hydrodynamic change induced by reclamation. Although this study is site-specific, the finding provides valuable information for sustainable management of channel-shoal systems in muddy-silt coast under intermittent or sequential land reclamation.

1. Introduction

Channel-shoal system, which can be found in global estuaries, coastal bays and tidal inlets, is a highly dynamic geomorphological system, whose size, shape and location change with local driving forces and variant sediment supply. The channel-shoal system serves as a critical component for socio-economic, environmental and ecological values. In the system, the natural or artificially excavated channels are often used for navigation. Shoals manifest as sinks of sediment, provide nursery, resting and feeding grounds for many species (Hibma et al., 2004) and act as a natural buffer against coastal flooding or erosion.

However, because of excessive new land demands for living and development in recent decades, reclamation has been rising at barbaric rates over many places in the whole world and China (Wang et al., 2014). As known, a channel-shoal system is vulnerable to shoreline hardening activities including land reclamation and seawall constructions. Profound influences of reclamation projects have been detected in tidal systems (Gao et al., 2014; Liang et al., 2015), sediment transport and morphodynamics (Davis and Barnard, 2003). Although the influence is mainly concentrated inside the tidal basin, responses can be found in the adjacent coastal areas even in the far-field sea (Song et al., 2013). Moreover, we are increasingly aware that cumulative impacts of human actives may lead to irreversible influence on the natural characteristics (Wang et al., 2015; Winterwerp et al., 2013), threatening the functions of original tidal basin and bringing the system to a negative state. For the past decades, morphologic shifts over many coasts have been identified worldwide. For example, completion in 1986/87 of an open storm-surge barrier in the inlets and of secondary dams in the landward of the Oosterschelde tidal basin shifted the formerly eroding basin into a sedimentation basin with a degrading intertidal area and silting up of channels (Mulder and Louters, 1994). Construction of a fill-type causeway that reduces the tidal prism at

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inlets, resulted in instability and closure of Blind Pass and Dunedin Pass, Florida (Davis and Barnard, 2003). In the Jiaozhou Bay, sequential reclamation triggered a switching from erosion pattern to accretion pattern due to the impact of land reclamation on the horizontal advection of suspended sediments (Gao et al., 2017). Although the convex profile shape remains in the accretional intertidal flat on the Jiangsu coast, the intertidal flat started to be narrower and steeper following sequential activities (Wang et al., 2012). These studies indicate that the influences of reclamation vary with the coastal geometries and reclamation project phases.

In general, tidal asymmetry leads to small spatial gradients in tide residual sediment transport, which causes morphodynamic development (van der Wegen, 2013; Stark et al., 2017). According to Jeuken and Wang (2000), in the tidal basin if the faster rising tide leads to a larger flood current, the system is referred as flood dominant or flood asymmetry. Otherwise, the tide is ebb dominant or ebb asymmetry. Variations in tidal asymmetry along the tidal basin are largely affected by the incoming tidal wave itself and coastal morphology, including the cross-sectional geometry of channel and the extent of intertidal flats (Dronkers, 1986; Friedrichs and Aubrey, 1988; Speer and Aubrey, 1985). Shallow channels with little intertidal storage tend to be flood dominant, whereas deep channels with large intertidal storage tend to be ebb dominant. The latter is able to flush out sediments from tidal basin, representing a more stable configuration. From this view, reclamation reducing intertidal storage is expected to switch tidal flow from ebb dominant to flood dominant, which will result in the channel siltation and degeneration of tidal basin. However, the intertidal storage effected tidal asymmetry in channel is highly depended on the elevation of tidal flats (or mean sea level) and the intertidal area location (Stark et al., 2017; Toublanc et al., 2015). The tidal flats located within the channel system are the flow-carrying part of channel which affect the hydrodynamic differently than the intertidal zones are side-basin of the channel system (Stark et al., 2017). Ebb dominance is significantly enhanced if the flow-carrying tidal flat is around or slightly above mean sea level. Conversely, flood dominance maintains if the tidal flat are situated low in tidal frame. Therefore, though the general principle of tidal asymmetry is deducted from numerous studies conducted on channel-shoal system, each system has its peculiarities, which provokes a high uncertainty of the roles of tidal flat in tidal asymmetry and sediment transport.

The Caofeidian sea is located in the northwest coast of the Bohai Bay, China (Fig. 1). It is developed from the abandoned ancient Luan River Delta (Kuang et al., 2012) and now characterized by a combination of natural deep channels and vast tidal flats. The coasts shift from uninterrupted to inlet-interrupted from west to east, as sandbars gradually formed during eastward movement of the Luan River. Three typical channel-shoal features developed along the coasts, i.e., tidal flat-channel-ridge system, tidal flat-sandbar-deep channel system and lagoon-inlet system. Since 2004, the Caofeidian sea has been experiencing a significant land reclamation. The reclamation was constructed in four phases shown in Fig. 1c, regarding as one of the largest reclamation projects in China. The most significant land reclamation took place at the tidal flat behind the Caofeidian barrier island (hereafter CFD) between 2006 and 2012 with the accumulated reclamation area of 230 km^2. Although the reclamation rate slowed down after 2012, most of the reclamation continued in the eastern part of the CFD. The accumulated reclamation area of 242 km^2 has been completed by 2016 and a target reclamation area of 310 km^2 is planned by 2020. Concerning the combination of complex coasts, channel-shoal features and high anthropic pressure, the Caofeidian sea provides a unique example for investigating sediment behavior under large-scale reclamation processes.

A few of efforts have been made to investigate the morphological responses to the Chaofeidian reclamation project in the last decade. To reveal the morphodynamic responses to the changing environment, researchers have investigated some data-driven methods (e.g., Jia et al., 1999; Tian et al., 2015; Wang et al., 1999; Zuo et al., 2014), which broadened our understanding of the formation and morphological development of channels and shoals in Caofedian sea. However, these data-driven methods can only reveal the combined impacts of sediment supply, climatic drivers and human interference. They are unable to separate the contribution of a single physical process (e.g., reclamation) to the morphological development.

The numerical modeling approach is superior to uncover the governing mechanisms of hydrodynamic and morphological changes. Based on numerical simulation, Kuang et al. (2012) concluded that morphological changes of Caofeidian sea in 2008 reclamation scenario had an acceptable rate of erosion and sedimentation. Lu et al. (2009) stated the flow velocity increases in front of Caofeidian foreland, and decreases in channels in the target reclamation scenario of 2020. Although these studies gave us the understanding the hydro-morphodynamics of Caofeidian sea under reclamation, the role of reclamation on channels and shoals was not illustrated. Furthermore, as the prevailing wave direct switched from S (south) in 1996–1999 to E (east) in

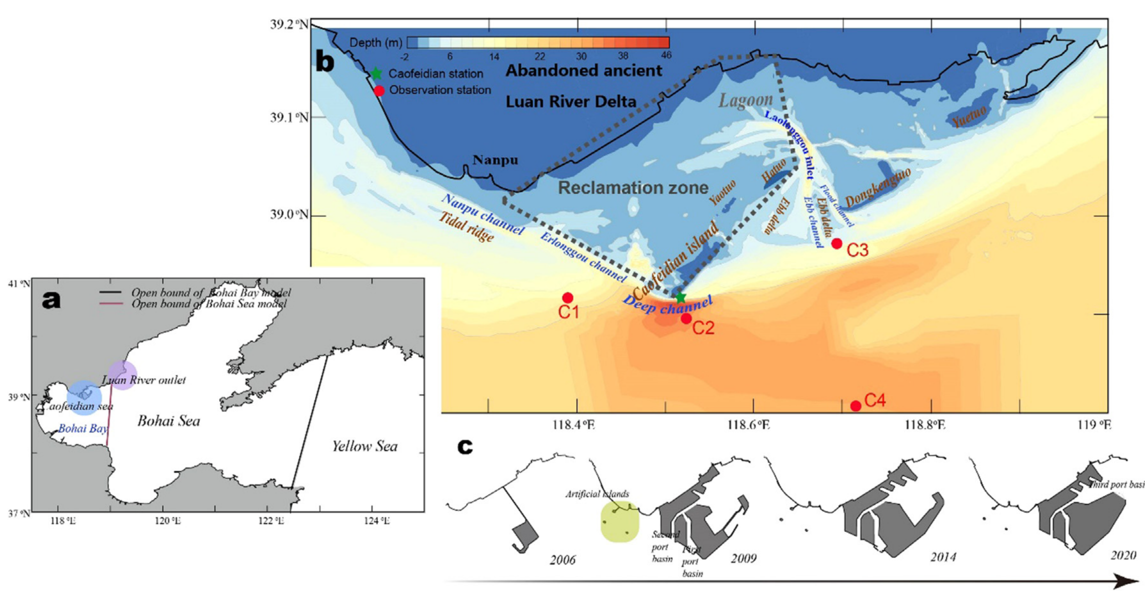

Fig. 1. Location map of **a** Bohai Sea, **b** the geomorphology of Caofeidian sea, and **c** the reclamation phases from 2006 to 2020.