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Morphological evolution of Jinshan Trough in Hangzhou Bay (China) from 1960 to 2011

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ABSTRACT

An extensive system of tidal channels, starting with Jinshan Trough in the east, is located along the north shore of Hangzhou Bay, China. This contribution investigates the morphological evolution of Jinshan Trough by using 17 bathymetric charts from a series covering a period of 51 years from 1960 to 2011. Three stages of evolution during this period are distinguishable based on the morphology and annual mean volume data. The first stage (1960–1987) is characterized by extension of the trough; the second stage (1987–1996) is a relatively stable period with some adjustments in the trough morphology; the third stage (1996–2011) is marked by the processes of erosion and deposition in the beginning of the period and a subsequent slow erosion process. Spatio-temporal variability of the trough was evaluated by using empirical orthogonal function (EOF) analysis. The first eigenfunction indicates that erosion is the main evolution process and there exists three stages similar to those distinguished from volume variations. The second eigenfunction mainly reflects erosion and deposition in the northwest part of the trough located in the flood tidal current shadow area of the artificial headland in Jinshan. The third eigenfunction mainly reflects annual fluctuations of erosion and deposition in the side slope at the artificial headland in Jinshan. A particularly intense erosion process occurred between 1996 and 1998. The major effects on morphological evolution in Jinshan Trough from 1960 to 2011 were investigated and tentative conclusions were presented. Continuous coastal reclamations in Jinshan had the most pronounced effect on the morphological evolution during the first and the second stages. The storm surge had a pronounced effect on the evolution at the beginning of the third stage.

1. Introduction

Tidal channels are important geomorphic units in tide-dominated estuaries characterized by funnel-shaped geometry. Quite often, they become centers of intense human activity and many contain harbors, shipping channels, land reclamation sites, dredging sites, *etc.* An essential requirement for maintaining the safety of marine constructions and local economic development is a thorough understanding of the morphological behavior of tidal channels, which can be affected by both natural and anthropogenic factors.

Van Veen (1950) gave the first definitions of ebb and flood channels in his work upon the tidal channel systems of the Netherlands. In early work, studies of tidal channel morphodynamics mainly focused on morphological descriptions, classifications, descriptions of hydrology and sediment, and processes of erosion and deposition (Wang et al., 2003). Later on, the development of in situ measurement technologies and increases in computational power provided opportunities for studies aimed at achieving a deeper understanding and predictions of the morphological evolution of estuaries and tidal channels. In general, modern scientific approaches can be tentatively divided into “top-down” and “bottom-up” strategies. The former approach, in respect to the tidal channel morphodynamics, is based on empirical estimations and thorough analysis of long-term morphological data, whereas the latter employs hydrodynamic models combined with sediment transport and morphodynamic modules (Karunarathna et al., 2008). Bottom-up models provide good insight into the mechanisms of tidal channel morphological evolution, especially in regard to short-term and local-scale changes (Blott et al., 2006).

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However, they have limited capabilities for assessing the long-term (decades or longer) geomorphologic evolution (Prandle, 2004; Townend, 2005; Wang et al., 2008). For that case, top-down models, in which interactions between geomorphology and sediment dynamics are analyzed, are more frequently used (Van der Wal and Pye, 2003; Blott et al., 2006; Karunarathna et al., 2008; Wang et al., 2008, 2013; Dai et al., 2013).

Jinshan Trough is located in the eastern part of a tidal channel system that has developed along the north shore of Hangzhou Bay. There is an abundance of manufactured constructions in the area, such as harbors and docks along the coast and operational oil pipelines fixed under the seabed across the trough, and such development underscores the need for studies on the morphodynamics in Jinshan Trough. Significant amounts of data on the geometry, hydrodynamics, suspended sediment transport, and sediment resuspension processes of the channel have been collected in recent decades (Yuan and Song, 1987; Cao et al., 1989; Liu, 1992; Yu and Fu, 1994; Yang et al., 2008). However, the long-term geomorphologic evolution of the channel has been scarcely documented and thus its understanding remains superficial.

In this paper, the spatio-temporal variability of Jinshan Trough topography is analyzed by using data from bathymetric surveys that were conducted between 1960 and 2011. On the basis of the results, some conclusions in regard to the influences of extreme natural phenomena and human interference on the morphological evolution of the tidal channels are made.

2. Study area

Hangzhou Bay is a funnel-shaped estuary with wide and shallow features; it is located between a longitude of 120°54′30″–121°50′42″E and a latitude of 29°58′27″–30°51′30″N. The area extends over approximately 5000 km^2 (ECCHE, 1992), and the average width is 100 km at the mouth in the east, where it connects to the East China Sea through the channels between the Zhoushan Islands, and 21 km at the top in the west, where the Qiantang River discharges into the bay. The estuary has a length of about 90 km. The Changjiang (Yangtze) Estuary is located adjacent to the bay in the north.

Hangzhou Bay is a typical macro-tidal estuary with a tidal range of 3–4 m at the mouth and 4–6 m further upstream (Xie et al., 2009). Tidal waves enter the bay from the East China Sea and propagate in the south–east direction. Owing to the funnel-shaped geometry and the Coriolis force, ebb and flood currents are asymmetric, namely, the former dominates in the south, while the latter dominates in the north region of the bay. Tidal currents are strong, especially in spring, when the maximum flood and ebb velocities reach values of 1.85–2.79 m s^{-1} and 1.44–2.35 m s^{-1}, respectively (Ni et al., 2003).

Sediment in Hangzhou Bay mainly comes from the Changjiang Estuary (Cao et al., 1985), and sediment transport processes have exerted a profound influence on the evolution of Hangzhou Bay (Su and Wang, 1989). The suspended sediment is transported in the bay under the control of tidal dynamics. There are three regions with high sediment concentrations; one is located in an area of sandbars at the top of the estuary, the second is located in the southern tidal flat area, and the third is located in the northeastern part of the mouth. There are also two regions with low sediment concentrations; these include an area consisting of tidal channels in the southeast and an area in the northern part of the bay (ECCHE, 1992).

The following three distinctive morphological units can be distinguished at the bottom of Hangzhou Bay: a shallow shoal, located at the mouth; a tidal channel and sand ridge system in the middle part; and a sandbar region at the top (Feng et al., 1990). The tidal channel system along the north shore of Hangzhou Bay is about 65 km long and 2 km wide, and it begins at Dajinshan Island and Xiaojinshan Island and ends at Ganpu (Fig. 1). It is generally accepted that the tidal channel system has formed and developed in response to flood current scouring (Wang, 2012).

Jinshan Trough is located in the eastern part of the tidal channel system. The trough begins at Dajinshan Island and Xiaojinshan Island and generally extends along the NEE–SWW direction (Fig. 1). The width of the trough becomes gradually narrower from east to west. The north side slope is steeper than the south side. The area that is deeper than 15 m is about 11 km long and 2 km wide, and the maximum depth of the trough is more than 50 m. There are also several scouring holes deeper than 30 m in this area.

3. Materials and methods

3.1. Data collection

Ever since the Shanghai municipal government decided to construct a petrochemical plant in Jinshan in 1972, bathymetric surveys of Jinshan Trough have been carried out almost every 2 years. A total of 15 bathymetric charts from the surveys for the following years were analyzed: 1972, 1976, 1980, 1981, 1982, 1983, 1985, 1987, 1988, 1990, 1992, 1994, 1996, 1998, and 2000. All these charts employ the Beijing 1954 coordinate system, a map scale of 1:10,000, and Gauss–Krüger Projections, and they relate to the same datum (Wusong Height Datum). Thus, conversion errors were not encountered. Water depth measurements were carried out every 100 m and had an error of 0.1 m. Since most of the surveys were accomplished in winter, discrepancies resulting from seasonality were minimal, which facilitated the comparative analysis. Two additional sea charts from the years 1960 and 2011 were included in the analysis. Both of them involved Mercator projections and were related to the lowest astronomical tide (LAT) datum. They employed the Beijing 1954 and CGCS2000 coordinate systems, and map scales of 1:50,000 and 1:25,000, respectively. Vertical error of the depth measurements was also 0.1 m.

In addition to that, we used tide level data from 1970 to 2005 from the Zhapu Hydrological Station and satellite data covering the study area (Qiantang Estuary and Hangzhou Bay) from the years 1960, 1970, 1980, 1995, 2005, and 2014 (data available at www.usgs.gov).

3.2. Data processing and analysis

Bathymetry data were processed on the ArcGis9.3 platform. First, the water depths described in the above charts were digitized. Second, the coordinate system, projections, and datum of the sea charts were transformed into those of the bathymetric charts. Third, a digital elevation model (DEM) with a resolution of 100 m × 100 m was produced for each chart by using the kriging interpolation method. Lastly, the DEMs were clipped to the same size and coverage area. On the basis of the DEMs, topographic comparisons, volume calculations, and empirical orthogonal function analysis were performed.

Empirical orthogonal function (EOF) analysis is a statistical method that can extract information from large datasets. This type of analysis, which is also referred to as a principal component analysis, solves the "eigenvalue problem" in which the variations in the data are statistically partitioned into orthogonal spatial eigenvectors (Emery and Thomson, 2001; Lane, 2004). This analysis decomposes the temporal and spatial dependence of the data by considering data as a linear combination of the corresponding functions of time and space. The eigenvalues are ranked based on the variability percentages. A detailed description of this method can be found in a statistics textbook (Jackson, 2003). Assuming that

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