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Observations and analysis of giant sand wave fields on the Taiwan Banks, northern South China Sea

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ABSTRACT

Understanding sand wave dynamics is of importance in marine science and also has relevance in engineering. Giant sand wave fields (wave heights up to 10 m) are not common and thus have been relatively rarely studied. This paper presents the first study on bedform changes related to giant sand wave geomorphology on the Taiwan Banks. Using data from three repeated multi-beam bathymetric surveys (2011, 2012 and 2013) and a spatial cross-correlation method, different sand transport patterns are obtained. Classical crest-perpendicular migration is observed in the small sand waves with migration rates of 1–5 m/a, and migration is parallel with the current direction. However, the giant sand waves are immobile over the observed periods, and along-crest transport sand transport has been observed that is perpendicular to the predominant current direction. Statistical results support these findings and thus illustrate a type of sediment transport pattern that differs from other sand wave fields around the world. It is concluded that the giant sand waves act as a bathymetric obstacle, thus changing the direction of bottom currents flowing over them, resulting in a change in sediment transport pattern on the Taiwan Banks.

1. Introduction

The bottom of many tide-dominated continental shelves is covered with regular large-scale patterns of elongated bedforms (Off, 1963; Liu et al., 1998; Liao et al., 2008; Wu et al., 2010). Their wavelengths range from several hundred meters to a few kilometers, with amplitudes in the order of meters (Allen, 1968). Their formation and migration are closely related to tidal currents, with sand ridges (sand banks) forming as rhythmic series oriented parallel with the current direction, while sand waves form perpendicular to the current direction (Off, 1963; Beldenson et al., 1982; Stride et al., 1982; Amos and King, 1984). Sand waves are dynamic, with the ability to migrate tens of meters per year, thus posing potential hazards to engineered coastal structures such as navigation channels, pipelines and wind farms (McCave, 1971; Berne et al., 1988; Dorst et al., 2011). Hence, sand wave behavior is of interest to marine scientists and engineers.

There are two basic research approaches used when investigating sand wave dynamics: seabed observations and models. Models provide generic knowledge of sand waves and can be used to study the effects of various hydrodynamic components (i.e., Hulscher, 1996; Németh et al., 2002; Besio et al., 2003; Németh et al., 2007; Campmans et al., 2018). Observations provide more direct information on the actual bedform shapes and changes over time at a measured location (Terwindt, 1971; Langhorne, 1981; Williams, 1995; Anthony and Leth, 2002). With the increasing resolution and positioning accuracy of observational equipment in recent years, remote sensing of the seabed has become more reliable (Knaapen, 2005; Dorst et al., 2009; Van Landeghem et al., 2009). Sand wave migration is usually expressed as horizontal displacement over time, achieved by comparing repeated surveys in both plane (crest) and cross-sectional (profile) shapes (i.e. Van Dijk and Kleinhans, 2005; Barnard et al., 2011). However, these lack comprehensive analysis of 3-D bathymetric data. To improve this methodology, researchers have adopted an effective cross-correlation method to detect geodetic deformation of bedforms (Duffy, 2005). The migration vectors obtained can be overlain upon bathymetric data, thus providing more detailed characteristics of sand wave migration. This method has now been widely used and further developed with the use of observational data from Acoustic Doppler Current Profiler (ADCP) backscatter and remote sensing inversion (i.e., Buijsman and Ridderinkhof, 2008). More environmental parameters have also been introduced into this method (i.e., Damen et al., 2018). Many observational studies indicate that sand wave migration is more complex than simply crest-

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perpendicular migration, with both oblique and rotated migration having been observed in complex bathymetries (Duffy, 2005; Barnard et al., 2006; Fenster et al., 2006).

Sand waves with meter-scale wave heights are very common, but giant sand waves (wave heights up to 10 m) are very rare. Such high-amplitude bedforms are known primarily from San Francisco Bay (Barnard et al., 2006) and Georges Bank (Jordan, 1962; Todd and Valentine, 2012). The giant sand wave field on the Taiwan Banks was first reported in the 1970s (Boggs, 1974), although subsequent studies developed slowly. This was likely related to limited data, resources and development of appropriate methods (Zhang, 1988; Lan et al., 1991; Liu et al., 1998; Cai et al., 2003; Hu et al., 2013). Remote sensing techniques are most effective for sand wave studies on the Taiwan Banks because of the shallow water depths and complex topography (Fan et al., 2009; Yang et al., 2010; Zhang et al., 2014). Multi-beam bathymetric data from recent studies has revealed co-existing sand waves on two distinct spatial scales on the Taiwan Banks. Yu et al. (2015) discussed the characteristics and distribution of the large sand waves, while Bao et al. (2014) focused on classification of the small sand waves. In terms of sand wave evolution, Du and Gao (2012) proposed a 1-D model, while other studies estimated sediment transport and sand migration rates empirically, with results in the 2–20 m/a range (Du et al., 2010; Lian and Li, 2011).

Most studies on the Taiwan Banks lack repeated high-resolution bathymetric data, resulting in a lack of comprehensive coverage of sand wave behavior in the study area. The purpose of this study is to present analysis of the characteristics and migration patterns of the two types of sand waves present based on repeated observational data. This is done to investigate how sand waves and sediments behave and interrelate in the study area.

This paper is organized as follows: We start with a brief description of the study area in Section 2. The bathymetric data and the methods used for analysis are introduced in Section 3. The results and interpretation are presented for the two types of sand waves in Section 4, and a discussion on sediment transport patterns of the co-existing giant and small sand waves is presented in Section 5. Finally, the conclusions are presented in Section 6.

2. Study area

The Taiwan Banks is a shallow continental shelf feature located in the south Taiwan Strait, between mainland China and the island of Taiwan, covering an area of 13,000 km^2. The average water depth of the Taiwan Banks is shallow (~20 m), and deepens gradually northward to the central Taiwan Strait. It deepens dramatically seaward to the continental slope (Fig. 1). It is a tectonically formed platform situated on a long-term uplifted plate (Ma and Liu, 1994), the top of which is covered by sediment. The sediments contain well-sorted medium to coarse sands, mixed with various shell debris and gravels (Lan et al., 1991; Cai et al., 2003).

Winds over the Taiwan Banks are dominated by the East Asia monsoon, and tropical cyclones in summer and autumn affect the weather significantly. Maximum wave heights of 4.7 m (winter) and 6.5 m (summer) have been recorded. Several typhoons pass through the Taiwan Banks every year, causing significant damage to the seabed patterns (Bao et al., 2014). Seasonal variations in the circulation are controlled by the China Coastal Currents, the northward South China Sea Current, and a branch of the Kuroshio Current (Jan and Chao, 2003; Wang et al., 2003; Hong et al., 2009) (Fig. 1). The tides on the Taiwan Banks are primarily irregular semidiurnal, and the M$_2$ tide is a predominant constituent with a range of 0.8–1.0 m/s (Liu et al., 1998; Du et al., 2010). The clockwise tidal currents of the southern branch and the anticlockwise tidal currents of the northern branch of the M$_2$ tide propagate from the Pacific Ocean into the Taiwan Strait, and meet north of the Taiwan Banks.

3. Data and methods

3.1. Bathymetric data acquisition and model construction

Three repeated multi-beam echo sounder surveys (R2Sonic 2024, 200–400 kHz range, with 256 beams per ping) were carried out in the study area in 2011, 2012 and 2013. The sounding accuracy of the surveys meets the requirements of the S-44 special order of the International Hydrographic Organization (IHO, 2008). The valid coverage width of the multi-beam swath reaches ~100 m, which is roughly three times the water depth in the study area. A Veripos DGPS (Veripos Ltd., Aberdeen, United Kingdom) was used for positioning, with a horizontal accuracy of ± 10 cm.

The original multi-beam soundings were then processed using CARIS HIPS and SIPS software (Teledyne CARIS, Inc., 2014; Caris HIPS and SIPS, version 8.1.9; Laurel Technologies, Inc., 2013). This was achieved by: (a) applying a sound velocity correction; (b) applying a tide correction; (c) editing navigation data and altitude data; and (d) data cleaning. Ultimately, a digital bathymetric model (DBM) was constructed at an appropriate resolution (Zhao et al., 2015).

Fig. 2 illustrates the distribution of the repeated multi-beam survey lines, wherein the "Line-west" represents the three repeated survey lines (2011, 2012, 2013), being 120 km in length and 120 m in width. The "Line-east" represents two repeated survey lines (2012, 2013), being 100 km in length and 120 m in width. DBMs with 1 × 1 m^2 grid-size resolution were then constructed for the 2011, 2012, and 2013 bathymetric data of Line-west and Line-east.

3.2. Cross-correlation technique

Sand wave migration is characterized not only by a shift in sand wave crest-lines but also by seabed deformation. Following Duffy (2005) and Buijsman and Ridderinkhof (2008), we use an efficient cross-correlation technique to determine migration of sand waves on the Taiwan Banks. Given that there are two scatter datasets $f(x,y)$, $g(x,y)$ in space (Fig. 3a), a search window matrix is set with the size $W_x \times W_y$. The cross-correlation technique calculates a correlation coefficient within the window, and the normalized correlation coefficient is given as:

$$R_{k,l} = \frac{\sum_{x=0}^{W_x}\sum_{y=0}^{W_y}[f(x,y)-\bar{f}\,][g(x-k,y-l)-\bar{g}_{k,l}]}{\sqrt{\sum_{x=0}^{W_x}\sum_{y=0}^{W_y}[f(x,y)-\bar{f}\,]^2\sum_{x=0}^{W_x}\sum_{y=0}^{W_y}[g(x-k,y-l)-\bar{g}_{k,l}]^2}} \tag{1}$$

$(-M \le k \le M, k \in Z, -N \le l \le N, l \in Z)$

where M and N are search parameters along the x- and y-axis, respectively. The search window is then moved along the x- and y-axis within the range of the search parameters to obtain a correlation coefficient matrix R with size $(2M+1) \times (2N+1)$. Finally, the maximum correlation coefficient within the matrix R is found, to locate two data points with "maximum correlation" within the two datasets. In this paper, the repeated DBMs in different years are considered to be different datasets. The two data points with "maximum correlation" become the starting and end points of a vector (termed "migration vector") that indicates the sediment transport pathway between two observed periods.

Some pre-analysis of the cross-correlation analyzing fields are necessary so that suitable values for search window size and search parameters can be chosen. Two types of sand waves at distinct spatial scales are developed in the study area: giant sand waves (with a length of ~750 m), and small sand waves (with lengths of 30–100 m). Pre-analysis indicates that the former are almost immobile, thus, the cross-correlation technique is mainly used to detect migration of the active small sand waves. For quality control of the results, the sensitivity of the correlation technique has been studied for window sizes of 30, 60,