A combined method to calculate superimposed 2-D dune morphological parameters

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ABSTRACT: Two-dimensional (2-D) subaqueous dunes often superimpose on giant dunes, sand bars or sand ridges. Mega-ripples may also be further superimposed on the 2-D dunes. A combined method was developed to analyse the geometry of the 2-D subaqueous dunes in this case, including 2-D Fourier analysis, wavelet transform, zero-crossing analysis, and various filtering. The regional dominant orientation and individual geometry parameters of 2-D submarine dunes can thus be obtained automatically with input of bathymetries. This method was successfully applied with both synthetic and observed bathymetries.

1 INTRODUCTION

Two-dimensional (2-D) dunes are common rhythmic bedform in submarine environments. They are often superimposed on large sand bodies, such as sand bars, sand ridges, and giant dunes. They are not only the results of sediment transport processes but also indicate sediment transport processes. Bedform wavelength and wave height are used to predict bed roughness (Yalin and Lai, 1985; Wang et al., 2016), and bedform asymmetry and orientation indicates the net sediment transport direction (McCave and Langhorne, 1982; Van Wesenbeck and Lanckneus, 2000). The understanding of modern submarine dune evolution is important for the restoration of paleo-sedimentary environments of sedimentary structures in boreholes and rocks (Baas et al., 2016). The formation and movement of submarine dunes may threaten the safety of submarine pipelines and navigation. (Németh et al., 2003). Thus, the bedform dynamics are one of the key issues of sedimentology.

Quantitative analysis of bedform morphology is the basis of the bedform study. Bedform geometry can be quantitatively represented by a number of parameters, which are associated with two categories. The first category is related to the overall regional patterns. For bedforms in a region, there is a dominant orientation and the associated characterized wavelength. The second category contains individual geometry parameters, such as the position of dune ridge, depth of dune ridge, wavelength, wave height, symmetry, lee slope angle, etc of different 2-D submarine dunes.

The relationship between these parameters and the relationship between the parameters with environment factors (i.e., bed sediment grain size, water depth, current velocity) were highlighted and investigated widely (Yalin, 1964; Allen, 1968; van Rijn, 1984; Flemming, 1988). However, more data are still required for a comprehensive understanding of these relationships.

High-resolution multibeam bathymetry increases the volume and complexity of bathymetric data, and a number of methods has been proposed to automatically quantify the 2-D dunes morphology.

For the regional morphological patterns, two-dimensional Fourier analysis can convert water depth matrix into a 2-D power spectrum. The main wavenumber can be extracted to calculate the regional dominant orientation and wavelength of submarine dunes (Van Dijk et al., 2008; Lefebvre et al., 2011; Cazenave et al., 2013). Anisotropic covariance analysis is also applied on the basis that the covariance in the direction of 2-D dune crests is the smallest, and the range value of the semi-variogram model in the direction perpendicular to the dune crests is the regional dominant wavelength of the submarine dunes (Dorst, 2004; Pluymaekers et al., 2007; Van Dijk et al., 2008).

Zero-crossing analysis can be easily applied to calculate the individual geometry parameters of submarine dunes. However, it would be challenged by the superimposition of bedforms with different scales. Thus, separating bedforms of different scales is necessary. Based on the geostatistical analysis, bedforms at different scales can be obtained by Kriging interpolation in a variety of resolutions (Van Dijk et al., 2008). 2-D discrete Fourier analysis combined with Butterworth high-pass filtering can effectively eliminate the background topographic effects (Cazenave et al., 2013). However, the spectral leakage of this method tends to underestimate wave height (Van Dijk et al., 2017). Although wavelet transform is applied for one-dimensional profiles, it has an outstanding performance in separation of dunes at different scales (Gutierrez et al., 2013).

Different methods have good performance at different stages of 2-D dune morphology analysis. We create a combined method based on Matlab, including 2-D discrete Fourier transform, Wavelet transform, and zero-crossing analysis. With an input of coordinates and bathymetry data, the regional and individual geometry parameters of superimposed 2-D submarine dunes can be calculated automatically. The method was applied to a synthetic bathymetry, and two measured bathymetries. One is on a sand ridge off Jiangsu Coast, China, and the other is on a sandbank in the Dover Strait, UK.

2 METHODS AND MATERIALS

2.1 Methods

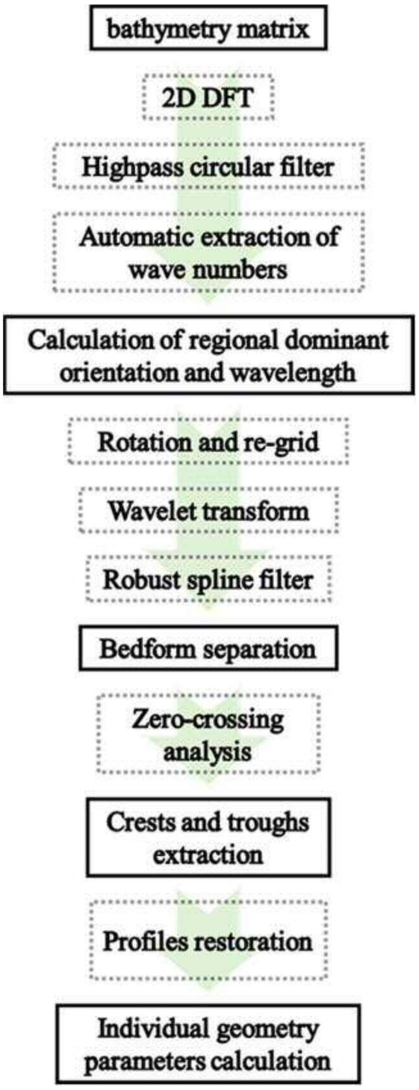

Figure 1. Flow chart of the combined method. Solid outlines indicate the products and functions of every steps. Dashed outlines indicate the processes and methods of every steps.

The method is divided into four steps. Firstly, it calculates regional dominant orientation and wavelength of the submarine dunes by 2-D discrete Fourier transform. Then, the matrix is rotated, re-gridded, and split into a number of 1-D profiles. Bedforms of different scales are separated by wavelet transform analysis. Thirdly, dune crests and troughs are extracted on the profiles by zero-crossing analysis. Finally, the individual geometry parameters are calculated on the profiles.

2.1.1 2-D Fourier analysis

Modified Cazenave et al (2013)'s 2-D Fourier analysis method is adopted to calculate the regional dominant orientation and the associated characterized wavelength. The power spectrum of the bathymetry matrix after the 2-D discrete Fourier transform is mirror symmetric and illustrate the spatial period of dunes. Circular filtering filters values near the coordinate origin in reciprocal coordinates. The line connecting two symmetrical wavenumbers passes through the coordinate origin. The regional dominant orientation of the 2-D dunes is the direction of the line. The distance from the selected wavenumber point to the origin of the coordinate is the reciprocal of the regional dominant wavelength of the dunes (Cazenave et al, 2013). The method provides an alternative parameter selection and ignores the influence of background topography. Here we detrend the bathymetry matrix in the x- and y-directions, in order to remove the influence of background terrain. We set the radius of the circular filter to 3 times the wavelength of interest and the power threshold of 90%.

2.1.2 Wavelet analysis

First, the bathymetry matrix is rotated according to the regional dominant orientation calculated by the 2-D Fourier analysis. Then the bathymetry matrix is re-grid and re-interpolate. Then it is split into 1-D water depth profiles which are perpendicular to the dune crestlines. The dune wavelengths of different scales can be extracted according to the wavelet transform power spectrum (Gutierrez et al, 2013). After the robust spline filter according to different wavelengths, three kinds of bedform profiles are separated.

2.1.3 Zero-crossing analysis

The zero-crossing analysis is performed to the bedform profiles of interest. The profiles separated by wavelet analysis are relatively smooth, but the effect of noise cannot be totally eliminated. A threshold for the distance of every other zero points is applied twice to eliminate the influence of noise. The threshold is set to 0.3 times the regional dominant wavelength. Then, the extreme point between adjacent zero points is extracted as the trough or crest point of the dune.

2.1.4 Dune geometry parameters calculation

The background topography can influence the geometry parameter calculation (Figure 2). We propose a method to solve this problem. Wavelength and wave height are defined as the distance from adjacent troughs (AB in Figure 2), and the vertical distance from the crest to the wavelength line (CD in Figure 2), respectively. Symmetry is the ratio of (AD - DB) to AB in Figure 2, and the lee slope angle in Figure 2 is ∠CAD.

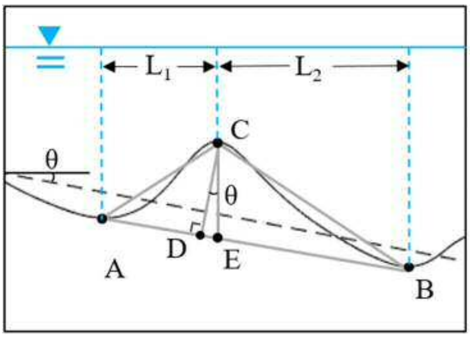

Figure 2. Schematic diagram of the definition of the dune geometry parameters. A and B are the troughs of the dune, and C is the crest. The blue line is the water line. The black dashed line represents the zero line of zero-crossing analysis. L_1 and L_2 are the horizontal distances of AC and BC.

2.2 Materials

2.2.1 Synthetic bathymetry

The synthetic bathymetry is constructed artificially, being the superimposition of bedforms with three different scales in the x-direction. The wavelength is 300 m, 16 m, and 1 m, respectively, and the corresponding wave height is 5 m, 1 m, and 0.1 m, respectively. The bathymetry in the y-direction is the same and repeated. Then, the matrix is rotated counter-clockwise by 45°, and a 200 m × 200 m rectangular bathymetry is selected. For the middle scale dunes, the large scale dunes is the background topography, and the small scale dunes is noise. The present method is applied to extract the morphological parameters of the middle scale dunes. By the comparison between the calculation results and the original settings, the method performance can be evaluated.

2.2.2 Field observed bathymetries

Two observed bathymetries are used for morphological parameters calculation using the present method. One is located on a sand ridge off Jiangsu coast, China. The collection was on January 19, 2017, using an R2sonic 2024 multibeam echo-sounder. After correction and swath data cleaning with CARIS HIPS and SIPS, the data were gridded to 0.5 m resolution. We chose a 100 m × 400 m rectangular area on the northern slope of the sand ridge which dunes superimpose on. Thus, removing the background sand ridge influences is crucial to calculate the dune morphological parameters.

A 500 m × 1000 m rectangular area on a sandbank in the Dover Strait, about 25 km east of Kent Coast, London, UK, was selected from marine data sets held by the UK Hydrographic Office (http://aws2.caris.com/ukho/mapViewer/map.action). The bathymetry was gridded with horizontal resolution of 1 m. The present method is to identify and separate the dunes in two scales, and the morphological parameters are computed for each scale dunes.

3 RESULTS

In terms of artificial data, the present method yields that the dominant orientation, average wavelength, and wave height of the middle scale dunes are 45.00°, 16.10 m and 1.04 m, respectively. They are very close to the settings of 45°, 16 m and 1 m, respectively. Thus, the method is accurate and feasible.

The dune extraction (Figure 3a) of the observed bathymetry from China shows that almost all of the dune crests are accurately extracted. The spatial distributions of wave length and wave height are shown in Figure 3.

Two scale dunes were extracted from the bathymetry in the Dover Strait (Figure 4). Red dots show the location of large scale dunes, with the dominant orientation, average wavelength, and average wave height of 135.37°, 187.50 m, and 1.99 m, respectively. However, for the small dunes, these values change to 95.50 °, 9.50 m, and 0.24 m.

4 DISCUSSION

4.1 Parameters selection of 2-D Fourier analysis

In the 2-D Fourier analysis, two parameters determine the accuracy of the extraction result, namely, being the radius of the circular filter and the threshold of wavenumber extraction. Cazenave et al. (2013) considered that the reciprocal of the radius of the circular filter is generally set to 10% of the long side of the bathymetry region. The length of the long side of the bathymetry area must be greater than 10 times the wavelength, suggesting that the reciprocal of the radius of the filter is greater than the wavelength of dunes. In this way, selecting more than 80% of the maximum peak power can meets the error requirement. However, the background topography of the observed bathymetry makes it difficult to select parameters. Combination of different parameter selections leads to different results, some of them being unreal. Thus, it is difficult to choose the correct wavenumber.

However, after detrending background topography, the results of different parameter combinations are consistent. In this way, we can set two fixed parameters. Thus, detrending does not only improve the selection of the wavenumbers, but also simplifies the selection process.

4.2 Correction of deviation of parameter calculation

Traditionally, bedform morphological parameters are determined based on the horizontal coordinates, in Figure 2, the wavelength and the wave height being $L_1 + L_2$ and CE, respectively. However, the background topography should be taken into account. The background topography is a flat slope with an anger of θ, which is parallel to AB. The actual wavelength is $(L_1 + L_2)/\cos\theta$, which is equal to AB, and the wave height is $CE*\cos\theta$, which is equal to CD. The relative error of the wave steepness (the ratio of wave height to wavelength) is $(\sin\theta/\cos\theta)^2$, which increases with θ. The relative error of the dune symmetry is $2*St*\sin\theta/Sy$, in which St and Sy are the wave steepness and symmetry, respectively. It increases as θ and St increase and Sy decreases.

The effects of background topography can not be neglected for area with large value of θ (i.e., ~10° or more), which is frequently associated with the lee slope of giant dunes. Assuming that St and Sy are 0.05 and 0.1, respectively, the relative error of the steepness and symmetry of the dunes with a slope of 20° would be 13% and 34%. To avoid errors caused by background terrain, we chose a revised method to calculate morphological parameters, as shown in 2.1.4. Thus, in this way, the geometry parameters of submarine dunes can be directly compared on different slopes of the background topography.

5 CONCLUSIONS

A combined method was developed to analyse the geometry of the 2-D subaqueous dunes, including 2-D Fourier analysis, wavelet transform, zero-crossing analysis, and various filtering. The regional dominant orientation and individual geometry parameters of 2-D superimposed dunes can thus be obtained automatically with input of bathymetries.

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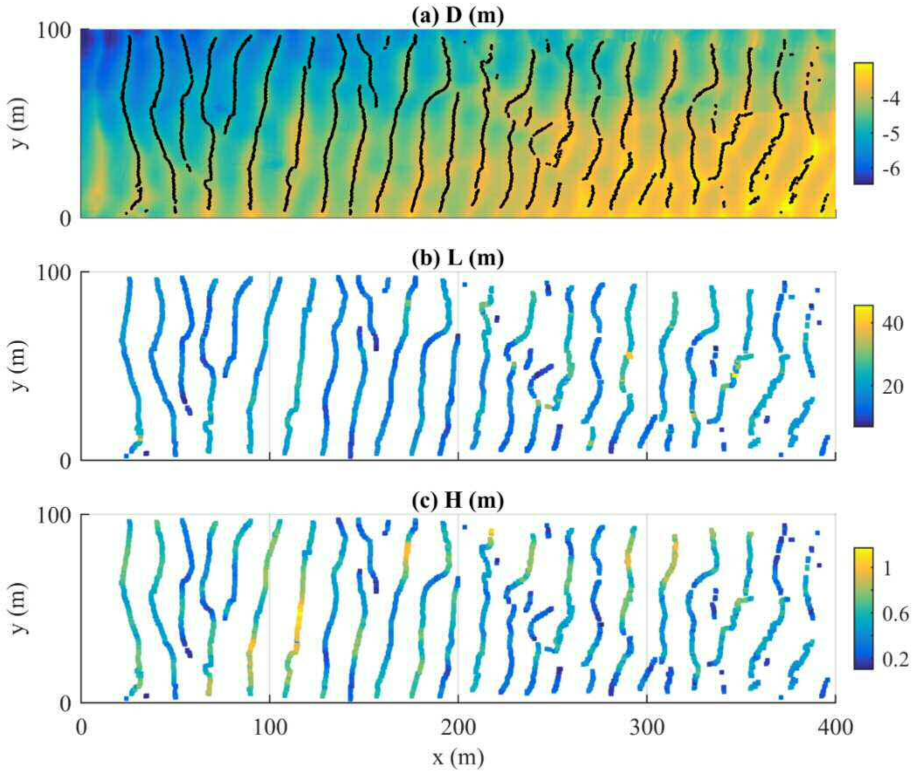

Figure 3. Dunes extraction of bathymetry from Jiangsu Coast, China and the Distribution of dune morphological parameters. (a) Dunes extraction (black dots mean the location of dune crest. The colour shows the water depth); (b) Distribution of wavelengths; (c) Distribution of wave heights.

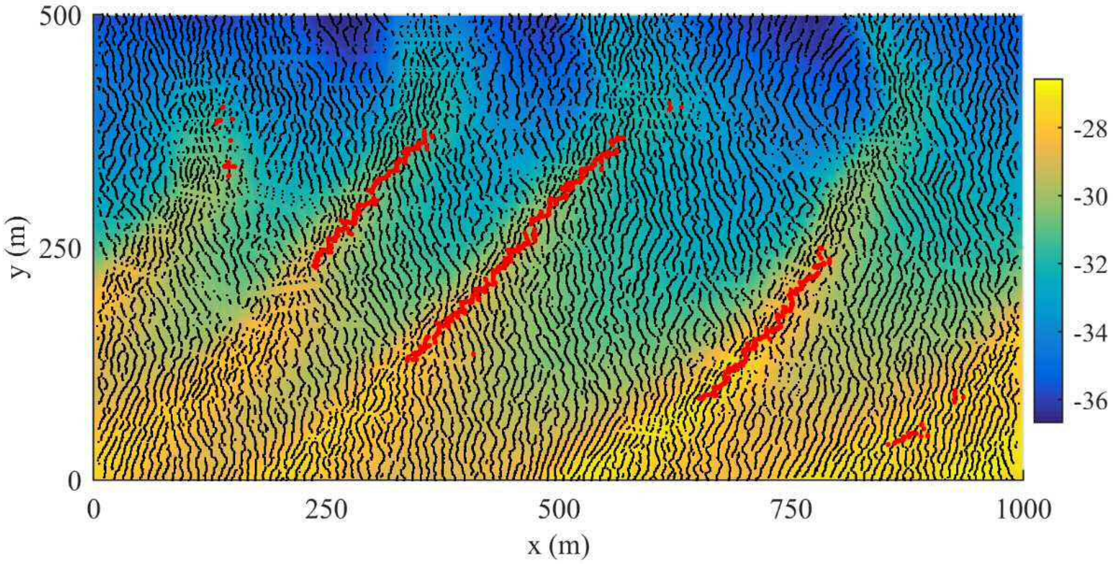

Figure 4. Dunes extraction of bathymetry from Dover Strait, UK. The colour shows the water depth. Black dots mean the location of small dune crests. Red dots mean the location of large dune crests.