Advances in Computer Science Research, volume 89
2019 International Conference on Wireless Communication, Network and Multimedia Engineering (WCNME 2019)

Segmentation Algorithm for Digital Sea-floor Terrain Based on Rolling Ball Transform

Jian Dong[1,2], Rencan Peng[1,2,*], Yang Chen[1, 3], Han Zhu[4], Guohui Liu[3] and Minghui Li[3]
[1]Department of Military Oceanography and Hydrography & Cartography, Dalian Naval Academy, Dalian 116018, China
[2]Key Laboratory of Hydrographic Surveying and Mapping of PLA, Dalian Naval Academy, Dalian 116018, China
[3]Chart Information Center, Tianjin 300450, China
[4]Sanjiang University, Nanjing 210012, China
*Corresponding author

***Abstract*—Based on the analysis of the essential principle of the two dimensional rolling circle transform algorithm, and by means of rolling circle transform dimensional extension, the paper has brought forward the conception of rolling ball transform. By which quantitative analysis has been done for marine topography included in DDM, and the segmentation algorithm for digital sea-floor terrain considering scale factor is erected. Some experiments that under the condition of VC++ have been done to validate the algorithm's validity. The experiments show that the algorithm could preferably identify and classify the marine topography, meantime, realize the segmentation of diversified sea-floor terrain in multi-scale factors according to buffer radius.**

Keywords—digital depth model; terrain segmentation; rolling circle transform; rolling ball transform; scale; algorithm

I. INTRODUCTION

DDM is a discrete expression of seabed topography in the form of matrix, it is easy to store and process by computer. Many digital seabed terrain analysis algorithms and computational programs are designed for DDM, and it has become a general data organization standard [1-2]. DDM contains a large amount of seabed topography and landform information, and the reasonable segmentation and interpretation of such information are of great significance for marine engineering, marine environment, biological breeding and military activities [2-3]. According to its morphological characteristics, DDM can be divided into three types of typical terrain. One is positive topography, such as cliffs, submarine volcanoes, mud volcanoes, reefs, etc. The other is negative topography, such as gully, gully, pit, etc. These topographies exist underwater and often form cliffs because of the erosion of ocean currents or lack of weathering forces. Another is flat terrain, which is common in both deep and shallow waters.

In recent years, many scholars have conducted researches on the segmentation of seabed topography, and some achievements have been made [4-8]. However, most of them analyze and divide the morphological characteristics (also known as topographic factors) of seabed topography at a single or fixed scale, which is unilateral and subjective in describing the real seabed topography. In order to describe the submarine geomorphology comprehensively and objectively, we should consider the interaction of various factors affecting the submarine geomorphology. Besides the influence of traditional topographic factors, scale factors are also the factors that must be considered in the submarine topographic segmentation. Due to the influence of DDM synthesis algorithm in the scaling process of DDM at different scales, the seabed topography and landform information contained in DDM is irreversibly lost to some extent [9-13]. In fact, different scales of DDM are different digital expressions of topographic and geomorphic information of the same seabed in the same sea area. Therefore, a seabed terrain segmentation algorithm based on original DDM considering scale factor is an effective way to achieve seabed terrain segmentation.

Buffer analysis is one of the basic spatial analysis functions in geographic information system (GIS) and an important method to measure the characteristics of spatial elements [9-14]. The two-dimensional rolling circle transformation based on buffer analysis function is widely used in concave-convex analysis of plane elements and extraction of minimum convex hull [10-11]. Based on the analysis of the essence of the two-dimensional rolling circle transformation algorithm, the concept of rolling sphere transformation is proposed by expanding the dimension of the two-dimensional rolling circle transformation algorithm. The rolling sphere transform is used to analyze the seabed topographic information quantitatively contained in DDM, and a digital seabed topographic segmentation algorithm considering scale factor is constructed. The correctness and validity of the algorithm are verified in VC++ environment. The results of the experiment show that the algorithm can recognize and classify seabed topographic morphology well, and can effectively segment various topographic types at different scales according to the change of buffer size.

II. SEGMENTATION ALGORITHM FOR DIGITAL SEA-FLOOR TERRAIN BASED ON ROLLING BALL TRANSFORM

In order to better explain the construction principle of the algorithm, the concept of buffer boundary transformation is introduced.

A. Buffer Boundary Transformation

If a three-dimensional spatial element is set T with a buffer distance of r, its corresponding buffer is defined as the set of all points that are not more than the distance from the spatial element T [12-13]. Namely:

$$B(T,r)=\{P(x,y,z)\,|\,\{d_e(P,Q_T)\,|\,Q_T(x_T,y_T,z_T)\in T\}\le r\} \quad (1)$$

Where, B is the buffer of space element T; $P(x,y,z)$ is any point on buffer B; $Q_T(x_T,y_T,z_T)$ is the sampling point on the spatial element T; $d_e(P,Q_T)$ is the three-dimensional Euclidean distance between P and Q_T. In two dimensions, the key of rolling circle transformation lies in the correct generation of buffer boundary on the left (right) side of line elements. As a special kind of three-dimensional space single valued surface, The coordinate values of one coordinate direction of DDM can be expressed by the single value functions of the other two coordinates [13-14].That is: $z_T=f(x_T,y_T)$ is the function relationship existing between coordinate values (x_T,y_T,z_T) of grid point Q_T (sampling point) on DDM. Using equation (1), and order $d_e(P,Q_T)=r$, then the coordinate value (x,y,z) of any point P on the boundary of DDM buffer has the following functional relationship:

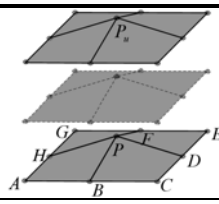
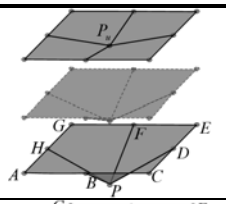
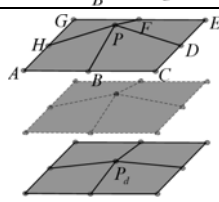
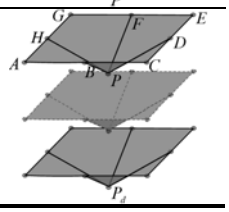
$$\begin{cases} z'=f'_{Q_T}(x,y)=f(x_T,y_T)+[r^2-(x-x_T)^2-(y-y_T)^2]^{1/2} \\ z''=f''_{Q_T}(x,y)=f(x_T,y_T)-[r^2-(x-x_T)^2-(y-y_T)^2]^{1/2} \end{cases} \quad (2)$$

Where, if $z'\ge f(x_T,y_T)$, than means (x,y,z') is above DDM, remember boundary point P_u on DDM buffer; otherwise, if $z''\le f(x_T,y_T)$, than means (x,y,z'') is below DDM, remember boundary point P_d on DDM buffer. Based on equation (2), DDM positive (negative) to buffer boundary transformation $K_U(r)$ ($K_D(r)$) is defined as followed:

$$\begin{cases} T\cdot K_U(r)=B'(T,r)=\{P_u(x,y,z')\,|\,z'=f'_{Q_T}(x,y)\,|\,Q_T(x_T,y_T,z_T)\in T\} \\ T\cdot K_D(r)=B''(T,r)=\{P_d(x,y,z'')\,|\,z''=f''_{Q_T}(x,y)\,|\,Q_T(x_T,y_T,z_T)\in T\} \end{cases} \quad (3)$$

Where, $B'(T,r)$ is the upper boundary of DDM buffer; $B''(T,r)$ is the lower boundary of DDM buffer.

TABLE I. ANALYSIS OF BUFFER BOUNDARY TRANSFORMATION CHARACTERISTICS

Transformation type	Positive terrain α	Negative terrain β
Positive Buffer Boundary Transform		
Negative Buffer Boundary Transform		

As shown in Table 1, positive terrain α and negative terrain β are composed of DDM grid cells $GFPH$, $FEDP$ and $PBAH$ respectively. Where, P is the topographic feature point, and the water depth of other grid points is equal. After the positive buffer boundary transformation $K_U(r)$, the relative distance between the topographic feature point P_u and the rest of the grid points in $\alpha\cdot K_U(r)$ remains unchanged (convexity and flatness preservation), while the relative distance between the feature point P_u and the rest of the grid points in $\beta\cdot K_U(r)$ decreases (concavity and flatness reduction); After the negative buffer boundary transformation $K_D(r)$, the relative distance between the topographic feature point P_d and the rest of the grid points in $\alpha\cdot K_D(r)$ decreases (convexity reduction and flatness), while the relative distance between the feature point P_d and the rest of the grid points in $\beta\cdot K_D(r)$ remains unchanged (concave and flatness preservation).

B. Principle and Characteristic Analysis of Rolling Ball Transformation

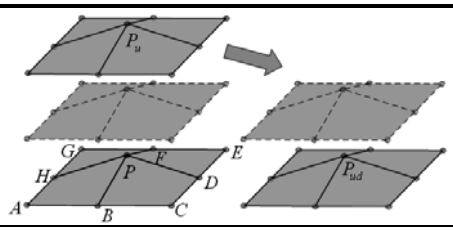
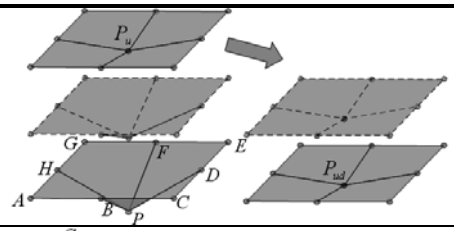
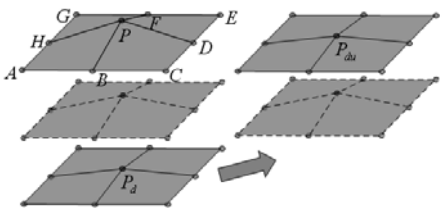
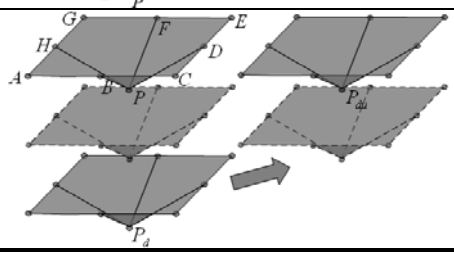
The rolling sphere transformation refers to a geometric transformation of a surface formed by rolling an infinite smooth sphere along the side of DDM in three-dimensional space. The rolling sphere transformation can be divided into positive (negative) directions. Mathematically, the rolling sphere transformation is equivalent to the combination of DDM positive (negative) to buffer boundary transformation $K_U(r)$ ($K_D(r)$). That is to say:

$$\begin{cases} T\cdot V_U(r)=T\cdot K_U(r)\cdot K_D(r) \\ T\cdot V_D(r)=T\cdot K_D(r)\cdot K_U(r) \end{cases} \quad (4)$$

Where, $V_U(r)$ is a positive rolling sphere transformation; $V_D(r)$ is a negative rolling sphere transformation; $T \cdot V_U(r)$ is DDM surface $T \cdot K_U(r) \cdot K_D(r)$ obtained by positive buffer boundary transformation $K_U(r)$ and negative buffer boundary transformation $K_D(r)$, respectively. That is, the surface formed by rolling the ball along the upper side of DDM; $T \cdot V_D(r)$ is DDM surface $T \cdot K_D(r) \cdot K_U(r)$ obtained by negative buffer boundary transformation $K_D(r)$ and positive buffer boundary transformation $K_U(r)$, respectively. That is, the surface formed by rolling the ball along the lower side of DDM.

As shown in Table 2, for positive and negative terrain, after the positive buffer boundary transformation $V_U(r)$, the relative distance between the topographic feature point P_{ud} and the rest of the grid points in $\alpha \cdot V_U(R)$ remains unchanged (maintain positive terrain), while the relative distance between the feature point P_{ud} and the rest of the grid points in $\beta \cdot V_U(r)$ decreases (reduce or fill negative terrain); after the negative buffer boundary transformation $V_D(r)$, the relative distance between the topographic feature point P_{du} and the rest of the grid points in $\alpha \cdot V_D(r)$ decreases (maintain negative terrain), while the relative distance between the feature point P_{du} and the rest of the grid points in $\beta \cdot V_D(r)$ remains unchanged (reduce or fill postive terrain).

TABLE II. ANALYSIS OF ROLLING BALL TRANSFORMATION CHARACTERISTICS

Transformation type	Positive terrain α	Negative terrain β
Positive Buffer Boundary Transform		
Negative Buffer Boundary Transform		

In rolling sphere transformation, the construction principle of positive (negative) to rolling sphere transformation $V_U(r)$ ($V_D(r)$) is the same. The size of buffer distance r determines the degree of its influence on the spatial geometry of DDM. There is a functional relationship between the level of leveling (filling) of positive (negative) terrain and buffer distance r as follows:

$$r - r' = r - \sqrt{r^2 - \lambda^2 \xi^2} \le \Phi \tag{5}$$

Where, r' is the distance between the center of the rolling ball and the plane where the positive (negative) topography is completely flattened; λ ($\lambda = 1, 2, 3...$) is the scale factor; ξ is the original DDM grid cell size (initial resolution); Φ ($\Phi \ge 0$) is the level of landform filling of positive (negative). The smaller Φ is, the higher degree of topography flattening (filling) is; conversely, the positive (negative) terrain level (fill level) the lower. In practical application, in order to ensure the segmentation effect of seabed topography, Φ is usually determined according to the limit error (confidence 95%) of bathymetric survey in the Code for Hydrographic Surveying. That is: $\Phi = 2\sigma$ (σ is the median error of Bathymetric Survey). At this point, the buffer distance r is further limited to $r \ge (\sigma + \frac{\lambda^2 \xi^2}{4\sigma})$ .The meaning of equation (5) can be understood as: After the forward rolling ball with buffer distance of $r \ge (\sigma + \frac{\lambda^2 \xi^2}{4\sigma})$ is transformed into $V_U(r)$, the positive (negative) terrain with convex (concave) length and width less than or equal to $2\lambda\xi$ in the original DDM will be completely

flattened (filled) (the error is less than the limit error of depth measurement).

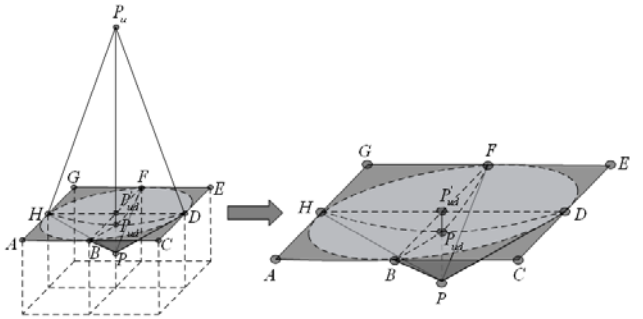


FIGURE I. CHARACTERISTIC ANALYSIS OF ROLLING SPHERE TRANSFORMATION

As shown in figure 1, P_u is the center of the rolling ball, P_{ud} is the terrain feature point corresponding to negative terrain β transformed by forward rolling ball $V_U(r)$, $P_u P_{ud}$ intersects plane $ACEG$ at $P_{ud}^{'}$, and the size of $P_{ud}P_{ud}^{'}$ reflects the filling degree of negative terrain β. If P_{ud} and $P_{ud}^{'}$ coincide ($P_{ud}P_{ud}^{'}$ is less than the limit error 2σ of bathymetry), then negative topography β is completely filled up. It should be noted that the change of buffer distance r will also cause the change of spatial position of topographic feature point P, and with the increase of r, PP_{ud} will gradually increase until unchanged (at this time $r \geq (\sigma + \frac{\lambda^2 \xi^2}{4\sigma})$).

C. Segmentation Algorithm for Digital Sea-floor Terrain Based on Rolling Ball Transform

Digital bathymetric model is essentially an ordered numerical sequence describing the spatial distribution of submarine surface morphology. From a mathematical point of view, DDM can be represented by an ordered set of values of two-dimensional matrix series [14-16]. That is:

$$T = \{z_{ij} \mid i \in [0, n-1],\ j \in [0, n-1]\} \tag{6}$$

Where, i, j is row and column number of grid unit; z_{ij} is the depth of the grid point; n is the number of grid rows and columns for DDM. Where z_{ij}^{ud} and z_{ij}^{du} are respectively the water depth values of the corresponding grid point (i, j) of DDM after positive and negative rolling ball transformation, then the water depth change value of grid point (i, j) can be expressed as:

$$\begin{cases} \Delta z_{ij}^{ud} = z_{ij}^{ud} - z_{ij} \\ \Delta z_{ij}^{du} = z_{ij} - z_{ij}^{du} \end{cases} \tag{7}$$

Where, Δz_{ij}^{ud} ($\Delta z_{ij}^{ud} \geq 0$) is the water depth change value of grid point (i, j) after transforming $V_U(r)$ by forward rolling ball; Δz_{ij}^{du} ($\Delta z_{ij}^{du} \geq 0$) is the water depth change value of grid point (i, j) after transforming $V_D(r)$ by negative rolling ball. Let $Terrain(i, j)$ be the topographic tri-state value of grid point (i, j) (-1 for negative terrain, 0 for flat terrain, and 1 for positive terrain), combined with the analysis of rolling sphere transformation above, the seabed topography can be divided into three parts according to the change of water depth of any grid point (i, j) on DDM:

$$\begin{cases} \Delta z_{ij}^{ud} > \xi, \Delta z_{ij}^{du} \leq \xi; then, Terrain(i, j) = -1 \\ \Delta z_{ij}^{ud} \leq \xi, \Delta z_{ij}^{du} \leq \xi; then, Terrain(i, j) = 0 \\ \Delta z_{ij}^{ud} \leq \xi, \Delta z_{ij}^{du} > \xi; then, Terrain(i, j) = 1 \end{cases} \tag{8}$$

Equation (8) above has a good distinguishing effect on simple positive, negative and flat topography as shown in table 1 and 2, while for more complex seabed topography, $\Delta z_{ij}^{ud} > \xi$ and $\Delta z_{ij}^{du} > \xi$ will occur, At this point, the seabed topography should be further divided according to the relative size relation of values of Δz_{ij}^{ud} and Δz_{ij}^{du}, that is:

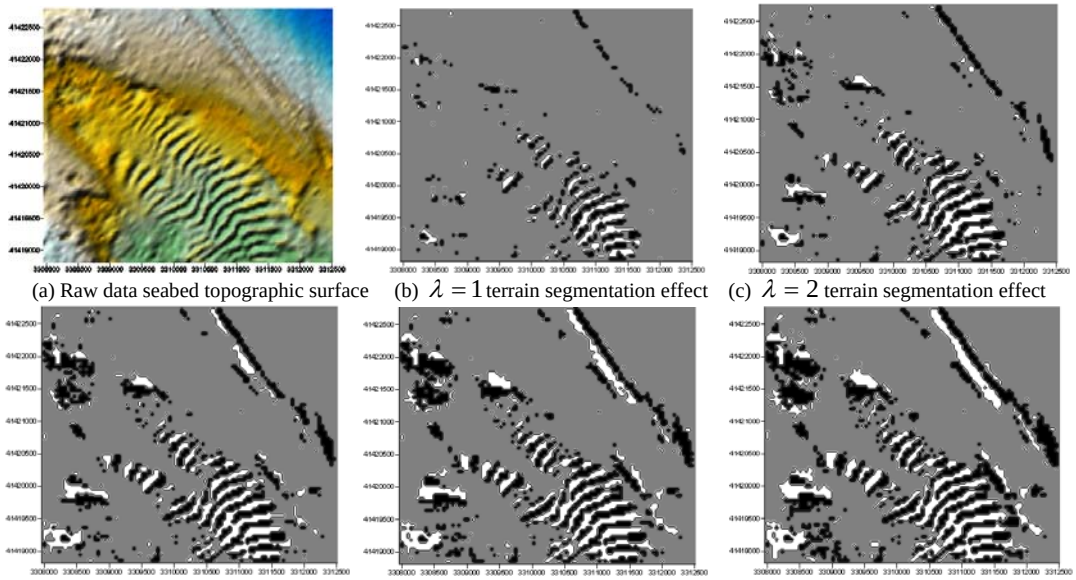
$$\begin{cases} \Delta z_{ij}^{ud} > \Delta z_{ij}^{du}; then, Terrain(i, j) = -1 \\ \Delta z_{ij}^{ud} = \Delta z_{ij}^{du}; then, Terrain(i, j) = 0 \\ \Delta z_{ij}^{ud} < \Delta z_{ij}^{du}; then, Terrain(i, j) = 1 \end{cases} \tag{9}$$

Where, if $\Delta z_{ij}^{ud} > \Delta z_{ij}^{du}$, then, any grid point (i, j) on DDM is greatly affected by the forward rolling ball transformation. According to the characteristics of the positive rolling ball to reduce or fill the negative terrain, the grid point (i, j) should be divided into negative terrain; On the contrary, if $\Delta z_{ij}^{ud} < \Delta z_{ij}^{du}$, than, any grid point (i, j) on DDM is greatly affected by the negative rolling ball transformation. According to the characteristics of the negative rolling ball to reduce or fill the postive terrain, the grid point (i, j) should be divided into postive terrain. For the case of $\Delta z_{ij}^{ud} = \Delta z_{ij}^{du}$, it means that the

positive (negative) rolling ball transformation has little effect on the grid points and belongs to flat terrain.

III. The Results and Analysis of the Experiment

To verify the correctness and effectiveness of the algorithm, in this paper, a digital seabed terrain segmentation algorithm based on rolling ball transformation is implemented in VC++ environment, and the generated experimental results are visualized and analyzed by using Surfer8.0 software. The data used in the experiment are Multi-beam Bathymetric Data in a certain area of the East China Sea, which contains 12774 discrete water depth points with a limit error of 1 m. Through the natural neighborhood interpolation algorithm in Surfer 8.0 software, the original DDM is generated with a resolution of 45 meters. The experimental environment is a Celeron (R) processor with a main frequency of 2.53 GHz and a memory of 512 M.



(a) Raw data seabed topographic surface (b) $\lambda = 1$ terrain segmentation effect (c) $\lambda = 2$ terrain segmentation effect

(d) $\lambda = 3$ terrain segmentation effect (e) $\lambda = 3$ terrain segmentation effect (f) $\lambda = 3$ terrain segmentation effect

FIGURE II. COMPARISON MAP OF TERRAIN SEGMENTATION EFFECT BETWEEN RAW DATA AND DIFFERENT BUFFER DISTANCE

The experiments were divided into five groups, and the original DDM was segmented by rolling ball transform for different scale factors. As shown in Figure 2, the results of terrain segmentation under the influence of original DDM data and different scaling factors are compared. Where, the white area represents positive terrain, the black area represents negative terrain, and the gray area represents flat terrain. It is not difficult to see from the figure that the rolling ball transform can better realize the recognition and classification of seabed topography, and the effect of terrain segmentation becomes more obvious with the increase of scale factor.

In addition, in order to further verify the effect of rolling sphere transform mesoscale factors on seabed topographic segmentation results, the number of grid points occupied by positive, negative and flat terrain in five groups of experiments is counted. The experimental results are shown in Table 3.

TABLE III. ANALYSIS OF EXPERIMENTAL RESULTS

Number of grid	Scale factor				
	$\lambda = 1$	$\lambda = 2$	$\lambda = 3$	$\lambda = 4$	$\lambda = 5$
Positive topography	391	938	1143	1334	1487
Negative topography	716	959	1132	1310	1464
Flat terrain	7593	6803	6425	6056	5749
The elapsed time (s)	0.019	0.110	0.503	0.972	2.412

It can be seen from the experimental results in table 3 that the rolling ball transform can achieve effective segmentation of all kinds of terrains at a certain scale. With the increase of scale factor, the number of grid points occupied by positive and negative terrains gradually increases, indicating that the effect of terrain segmentation becomes more obvious with the increase of scale factor. Combined with the change of grid points occupied by flat terrain, it can be found that the flat terrain between adjacent scales varies greatly in different scales. This is because the rolling sphere transformation is based on the simple segmentation of positive, negative and flat terrain, and the more complex seabed terrain is further segmented.

IV. Tag

Based on the construction principle of two-dimensional rolling circle transform and the dimension expansion of two-dimensional rolling circle transform, this paper constructs a segmentation algorithm for digital sea-floor terrain based on rolling ball transform. The effect of buffer distance on the spatial geometry of DDM is analyzed theoretically. The experimental results show that the algorithm can recognize and classify the submarine topographic morphology well. At the same time, the effective segmentation of various topographic types at different scales can be realized according to the change of buffer distance. However, it should be pointed out that DDM is quite different from land DEM in terms of data sources and application modes. Therefore, its terrain segmentation algorithm has many

requirements and characteristics different from land DEM. The model in this paper only studies the terrain segmentation algorithm of DDM from the perspective of spatial geometry, and does not take into account the special requirements of various applications too much, so it needs to be further deepened and improved in practical application.

ACKNOWLEDGEMENT

This research was financially supported by the National Natural Science Foundation of China, No. 41601498; the National Key R&D Program of China, No. 2017YFC1405505.

REFERENCES

[1] Shepard M. Smith. The Navigation Surface: A Multipurpose Bathymetric Database[D]. Durham, New Hampshire: University of New Hampshire, 2003.

[2] Feng-min TIAN, Ding-jie XU, Yu-xin ZHAO, An Interpolation Method for Constructing Undersea Grid-DEM [J]. Navigation of China, 2009, 32 (3):61-65.

[3] Bing-yuan LI, Bao-tian PAN, Jia-fu HAN, Basic Terrestrial Geomorphic Types in China and Their Circumscriptions [J]. Quaternary Sciences, 2008, 28(4): 535-543.

[4] Gang YANG, De-wen DU, Hai-long LV, Segmentation Algorithm for Digital Sea-floor Terrain [J]. Advances in Marine Science, 2004, 22(2): 204-209.

[5] Weszja J. A Survey of Threshold Selection Techniques[J]. Computer Graphics and Image Processing, 1978, 7(2): 259-265.

[6] Wei-chao CAO, He-ping TAO, Bo KONG, etc., Recognition of General Topographic Features in Qinghai — Tibet Plateau Based on GIS [J]. Bulletin of Soil and Water conservation, 2011, 31(4): 163-167.

[7] Cai-zheng WANG, Yao-dong YANG, Ya-li FENG, etc. Identification and detection of deep-sea obstacles and terrains based on image processing [J]. Journal of University of Science and Technology Beijing, 2011, 33(7): 777-784.

[8] Wei-chao CAO, He-ping TAO, Bo KONG, etc. Topographic Automatic Recognition Based on Optimal Topography Feature Space[J]. Journal of Wuhan University, 2011, 36 (11): 1376-1380.

[9] Chang-qing ZHU, Wen-zhong SHI. Spatial analysis modeling and principle [M]. Beijing: Science Press, 2006.

[10] A.H.J.Christensen. Cartographic Line Generalization with Waterlines and Medial-Axes[J]. Cartography and Geographic Information Science, 1999, 26(1): 19-32.

[11] Wang-jun GAO. Application of Bidirectional Buffer Model in Automated Cartographic Synthesis [D]. Dalian Naval Academy, 2009.

[12] Pei-de ZHOU, Algorithm analysis and design [M]. Tsinghua University Press, 2000.

[13] zhi-lin LI, Qing ZHU. Digital elevation model [M]. Wuhan University of Surveying and Mapping Science and Technology Press, 2000.

[14] Peng HU, Lian YOU, Chuan-yong YANG, etc, Map Algebra [M]. Wuhan University Press, 2002.

[15] Yan-chun LIU, Fu-ming XIAO, Jing-yang BAO, etc. An Introduction to Hydrography [M]. Beijing: Surveying and mapping publishing house, 2006

[16] Ren-zhong GUO. Spatial Analysis [M]. Wuhan University of Surveying and Mapping Press, 2000.