Research on Dem Construction Methods With Effective Integration of Topographic Feature Lines

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Research Article

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Abstract: In cities and other human activity areas, the implementation of various ground projects has resulted in significant changes in natural surface morphology, a prominent feature of which is the formation of a variety of discontinuous terrains, such as roads and building basements. In the process of DEM modeling of these landforms, traditional modeling methods produce obvious topographic distortions at topographic prominences, which limits the application depth of DEMs in these areas. To solve these problems, this paper proposes a DEM modeling method to enhance the expression of discontinuous terrain from the perspective of simplicity and convenience for application. The method is based on terrain data such as topographic feature lines, altimetric points, and contour lines. First, parallel feature lines are generated according to a certain distance. Then, vertices are inserted into the topographic feature line and the parallel feature line according to the specified step length, and the known altimetric points are selected from both sides of the original topographic feature line to estimate the height value of the vertices. Finally, by combining the topographic feature line, parallel feature line and other available topographic data for TIN construction, the result can effectively express the special topography of discontinuous terrain. In this study, a region in Nanjing City, Jiangsu Province, China, was selected as the study area to conduct a DEM construction experiment. The experimental results showed that the DEM constructed by this method could well express the morphological characteristics of discontinuous terrain, and the height accuracy of the construction results was also significantly improved compared with that of the conventional method.

Keywords: Digital elevation model (DEM); Topographic feature line; Parallel feature line;

Morphological characteristics; Precision

1 Introduction

The digital elevation model (DEM), as the digital expression of surface morphology (Burrough and McDonnell 1998;Aguilar et al. 2005), is one of the most important basic geographic information data. It plays a key data supporting role in geoscientific analysis and process simulations (Hutchinson and Gallant 2000; Pike 2000), and they have been widely applied to describe terrain characteristics (Fisher 1991; Hunter and Goodchild 1997) in hydrological (Moore et al. 1991; Murphy et al. 2008), environmental protection (Li and Chen 2005), natural disaster analyses (Claessens et al. 2005; Kawabata et al. 2010), as well as material and energy transmission in the city (Bottyan Z, Unger J., 2003; Ratti C, et al. 2002; Ratti C, et al. 2006; Maruyama T. 1999; Kusaka H, et al, 2001), urban rainfall and flood analysis (Fereshtehpour M., Karamouz M, 2018; Saksena S., Merwade V, 2015; Hsu Y. C et al, 2016). With the rise of smart cities, digital cities and other related strategies in recent years, DEMs in urban areas have been subjected to higher requirements on shape accuracy, update timeliness and information bearing.

Urban terrain is different from natural terrain in surface morphology. Strong and sustained human activities have transformed the city into complex terrain including natural terrain and artificial terrain, and continuous terrain and discontinuous terrain coexist alternately. Such discontinuous terrain brings great challenges to DEM modeling in this area (Li J, Heap A D,2014; Woodrow et al, 2016). Scholars have constructed and developed many representative DEM modeling algorithms in recent years, such as Yue Tianxiang's high-precision surface modeling method based on differential geometric surface theory (Yue, 2011; Yue et al, 2016; Yue et al, 2020), which is particularly well suited for continuously changing natural terrain. The polyhedral function

method (Chen et al, 2015; Chen et al, 2016) constructed by Chen Chuanfa is suitable for DEM modeling in the case of gross errors in elevation information, and Jiang et al.(2018) combined the high-precision surface modeling method with a slope algorithm and proposed a DEM modeling algorithm suitable for water erosion terrain. Hutchinson et al.(1989) , Yang et al. (2007) proposed a DEM modeling algorithm (ANUDEM) based on the thin plate spline method and vectorized river network data. These algorithms enrich the DEM modeling method system and improve the DEM modeling accuracy under certain conditions to a certain extent. However, some of the above algorithms have been clearly shown to be suitable for continuous natural terrain modeling at the time of design, while some algorithms have not yet effectively undergone usability analysis in discontinuous terrain areas.

Some scholars have applied DEM modeling algorithms to some special terrain objects. For example, Wang Chun et al. (2009), Zhao Weidong et al. (2013) , Yang et al. (2005) and others have proposed feature embedded DEM (FE-DEM), terrace DEM, and so on. These new DEM models can ensure the local shape feature of the special surface. Although these studies have achieved good results in some special terrains, their defects are also very obvious. First, they are difficult to popularize on a large scale; second, they involve a new data structure and complex construction algorithm, so it is difficult to popularize and use them widely.

The above analysis suggests that to improve the expression effect of discontinuous terrain in urban areas, we should pay attention to two aspects: first, integrating the information of discontinuous terrain boundaries effectively; second, designing methods that are simple and easy to apply. This paper presents a method based on easily obtained topographic feature lines as a data source, and the parallel lines are generated according to a certain distance parameter. Then, the

altimetric points on both sides of the feature line are used to assign the height value to the vertices of the topographic feature lines and parallel lines. Finally, these topographic feature lines and parallel lines are used as constraint information for DEM construction. Tests carried out in this paper show that the new method can clearly express the morphological characteristics of discontinuous terrain.

2 Study methods

In cities and other areas with many discontinuous terrains, the main way to produce DEMs is to construct Triangulated irregular network (TIN) based on a large-scale topographic map. However, in the current TIN construction methods, the topographic lines cannot be expressed precisely, which leads to distortion of the expression of discontinuous terrain. This problem is illustrated in Figure 1. When topographic feature lines are used in TIN construction, some vertices are inserted into the feature lines, and it is necessary to estimate their height values. In the current TIN processing method, the height value of the vertices on the feature line is calculated by the altimetric points on both sides of the topographic feature line (for example, points A and B in the figure), which is very unreasonable for areas with a significant height difference on both sides of the topographic feature line. The result is that gentle slopes are formed on both sides of the feature line, which cannot effectively express the morphological characteristics of the discontinuous terrain.

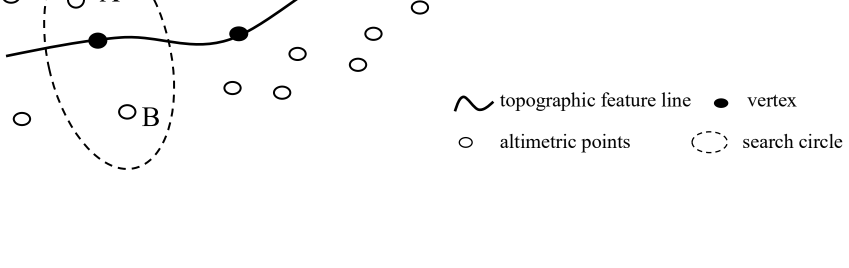


Fig. 1 Height calculation of vertices in the topographic feature line

The main reason for the above problems is that although the topographic feature line is the boundary line of discontinuous terrain, since one vertex cannot record two height values, a single boundary line cannot express the difference in elevation at the discontinuous terrain. In fact, there should be at least two lines called topographic feature lines in any discontinuous terrain on the natural surface. As shown in Figure 1, both lines are required to express the discontinuous terrain effectively and clearly.

According to the above analysis, the feasible way to solve the above problems is to generate a feature line based on the existing topographic feature line, which can be called a parallel feature line. Then, the original topographic feature line and parallel feature line are combined for DEM modeling. The detailed implementation process is listed as follows. First, for each original topographic feature line, the height difference on both sides of the topographic feature line is calculated based on the altimetric points within a certain range on both sides of the line to determine whether the difference is greater than the specified threshold value. If so, the current topographic feature line is marked for processing later. Then, for each marked original topographic feature line that needs to be processed, the parallel feature line of the current original feature line is generated on the side with the lower height value, and vertices are inserted into the topographic feature line and its parallel feature line according to the specified step size parameter. Then, the height value of each vertex is calculated according to the known altimetric points around them. Finally, after the height values of all the vertices are calculated, the original topographic feature lines and their parallel feature lines are output to construct the TIN together with other terrain data. If necessary, the TIN can be further converted into a regular grid DEM.

In the above implementation steps, the elevation estimation of vertices in the original topographic feature line and its parallel feature line is the core of this algorithm, and this process can be further described in detail as follows. First, the first vertex of the original topographic feature line is taken as the first vertex to calculate the height value. Then, by taking the current vertex as the center of the circle and the original topographic feature line as the reference, a search semicircle is generated according to the specified radius parameters on the side where there is no parallel feature line. Finally, the number of altimetric points falling into the search semicircle is counted, and the height value of the current vertex to be calculated is calculated according to the inverse distance weighting algorithm; the height values of other vertices are calculated in a similar way. If the number of altimetric points in the search semicircle generated for the first time is insufficient, the radius of the search semicircle can be further expanded until the altimetric points satisfying the calculation can be found.

Compared with the traditional method, the main characteristic of the height value estimation method for vertices in this research is that the altimetric points are selected on only one side of the topographic feature line, as shown in Figure 2. The solid circle in the figure represents the altimetric points used to calculate the vertex height value of the original topographic feature line (black solid line), while the hollow circle represents the altimetric points used to calculate the vertex height value of the parallel feature line (black dotted line).

This method can avoid adopting altimetric points on both sides of the topographic feature line participate in the calculation of the height value of the feature line vertex at the same time. However, the altimetric points (hollow triangle in Figure 2) between the topographic feature line and parallel feature line cannot participate in the calculation of the vertex height value.

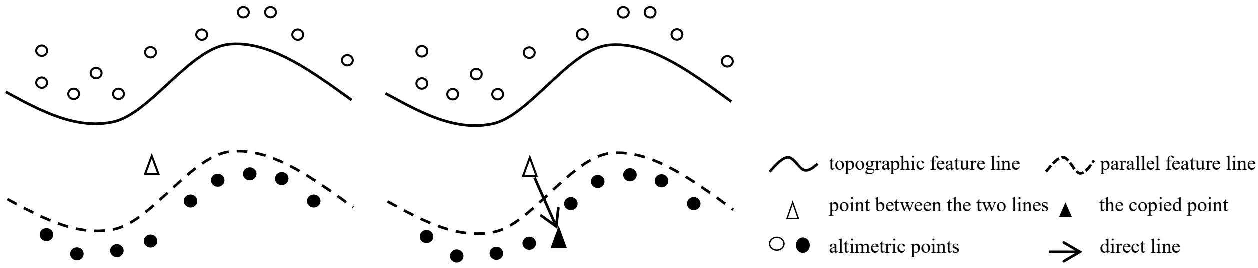


Fig. 2 Spatial relationship between topographic feature line and parallel feature line

In this research, parallel feature lines are generated on the side with low height values of feature lines. Therefore, the hollow triangle in Figure 2 should be used to calculate the height value of vertices in the parallel feature lines. From the point of view of easy operation, a solution is designed in this study that takes the parallel feature line as a reference and copies a point to its other side, as shown in Figure 2. The operation of the duplicate point is carried out dynamically with the height value calculation of the feature line vertices; that is, for the same altimetric point to be copied, when the vertices to be calculated are different, the positions to be copied are different to ensure that the spatial distances between the copy point, the original point and the point to be calculated remain unchanged.

3 Research area and data

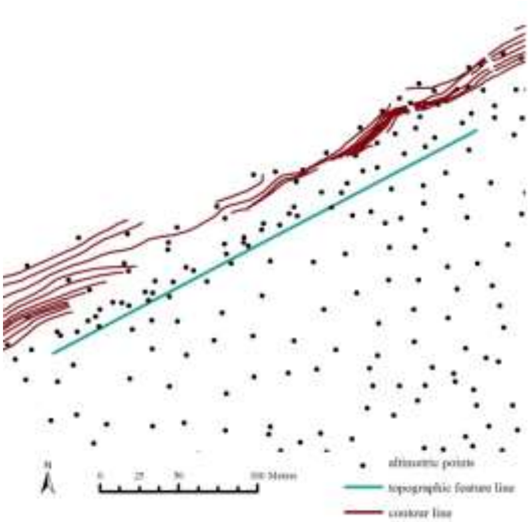
In this study, a study area was selected in a suburban area of Nanjing City, Jiangsu Province, China. The region contains the city suburbs and is close to the Yangtze River. Its original terrain is a gentle hilly terrain. Following the transformation of various human activities and projects, this area contains a staggered distribution of natural terrain and artificial terrain. There are various and rich types of discontinuous terrain, which can meet the modeling requirements of this study. In the

study area, this paper selects four discontinuous terrains to carry out DEM modeling experiments, the first one (Terrain-A) is located between a road and a factory; the second one (Terrain-B) is platform terrain, where the topographic feature line is circular; the third one (Terrain-C) is a quarry field, where the topographic feature line is between the quarry filed and the hillside; and the last one (Terrain-D) is located under the hillside foot, there are two topographic feature lines that are approximately closed and a building site lies between them. (Figure 3). The topographic feature line and elevation information of each discontinuous terrain are listed in Table 1.

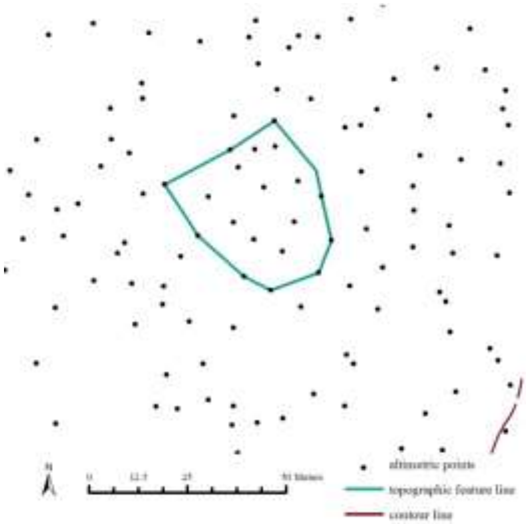
The basic data used in this study are extracted from a 1:500 scale topographic map, which is produced by the local surveying and mapping department according to large-scale production specifications. The topographic map contains basic terrain information such as altimetric points, contour lines and topographic feature lines, and auxiliary information. It is necessary to preprocess the original topographic map data before DEM modeling, and the main goal is to extract the data needed for modeling in the experimental area, including altimetric points, contour lines and topographic feature lines that mark the location of discontinuous terrain. This part of the work is completed manually based on the ArcGIS 10.2 software platform.

Tab. 1 General information of topographic feature lines in the test areas

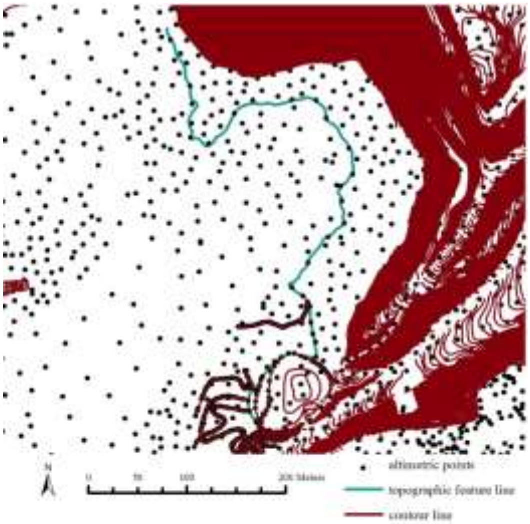
	Length of the feature line	The max elevation difference	The minimum elevation difference	The average elevation difference
Terrain-A	303.3	1.9	2.3	2.1
Terrain-B	127.5	2.65	2.4	2.7
Terrain-C	741.2	1.27	11.8	5.6
Terrain-D	723.5	9.63	6.9	2.9



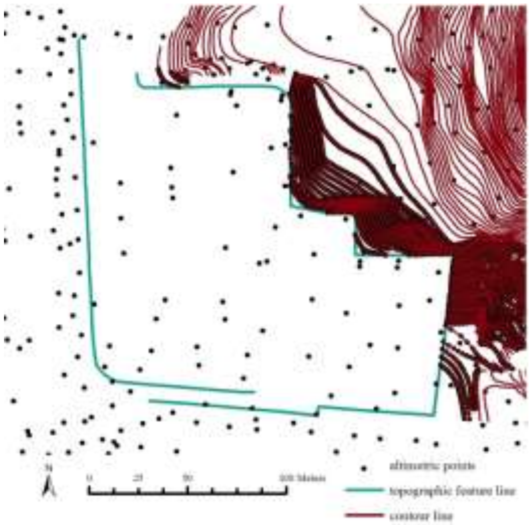
(a) Terrain-A



(b) Terrain-B



(c) Terrain-C



(d) Terrain-D

Fig. 3 Topographic map of the study area

4 Result analysis

For the four discontinuous terrains selected in this paper, DEM construction is carried out based on the method proposed in this paper. In addition, to compare and analyze the accuracy advantage of the DEM constructed by this method, the DEM constructed by the traditional method is taken as

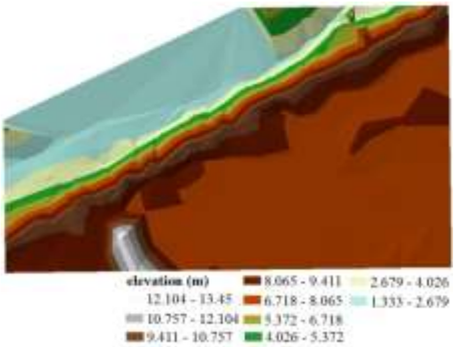
the comparison result. Since the data provided in this study include altimetric points, contour lines and topographic feature lines, this paper uses the method of constructing TIN as the comparison method.

In this paper, the traditional method and the new method are compared and analyzed from qualitative and quantitative perspectives. The qualitative analysis includes the comparative analysis of TINs constructed by the two methods and the mountain shadow map generated based on the two results. The main purpose of qualitative analysis is to analyze whether the constructed DEM can effectively express the mutation site of the study area shape features. Quantitative analysis is also carried out from two aspects. First, the elevation information on the feature line is quantitatively expressed, and the second is a height accuracy analysis based on the accuracy verification point. The main purpose is to verify the height accuracy advantage of the DEM construction method proposed in this paper.

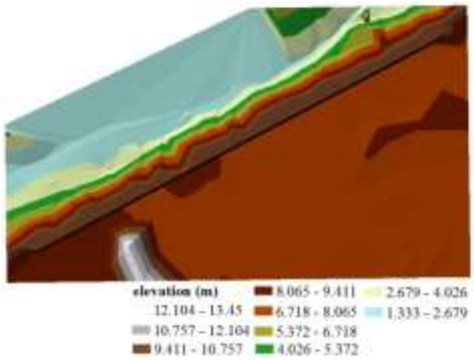
4.1 TIN analysis

Figure 4 shows the comparison between the TIN constructed by the conventional method and the method proposed in this research. The method in this paper has obvious advantages over the conventional method in morphological expression. In some areas with relatively simple terrain (Terrain-A and Terrain-B), an obvious slope surface is formed on one side of the topographic feature line in the DEM constructed by the conventional method. In addition, the slope generated near the feature line presents an irregular zigzag form due to the uneven distribution of altimetric points used for modeling. In contrast, the method proposed in this paper has a good effect in Terrain-A and Terrain-B, where the terrain is relatively simple. The figures show that the results of the new method basically form an obvious boundary at the topographic feature line in these regions and that the

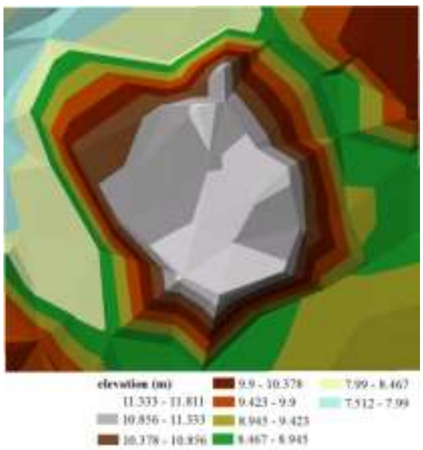
height difference between the two sides is obvious. For areas with complex terrain changes, such as Terrain-C and Terrain-D in this paper, the results of conventional methods cannot express the surface morphology well, and some local areas also have the phenomenon of concave terrain crossing the feature line. This is because there is a lack of elevation information points on the higher side of the terrain and because the point with a lower height value on the other side is used in the modeling process. The results based on this method can avoid this phenomenon and express discontinuous terrain well.



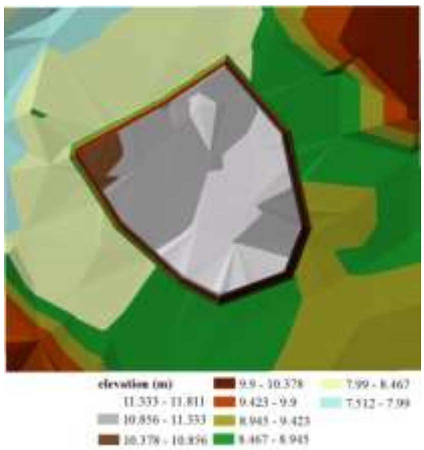
(a) conventional method in terrain-A



(b) new method in terrain-A

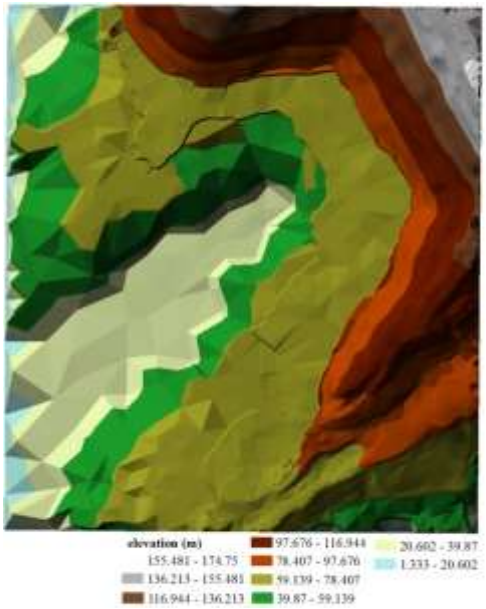


(c) conventional method in terrain-B

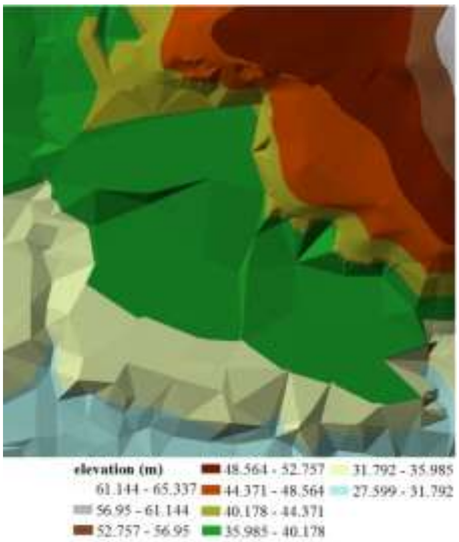


(d) new method in terrain-B

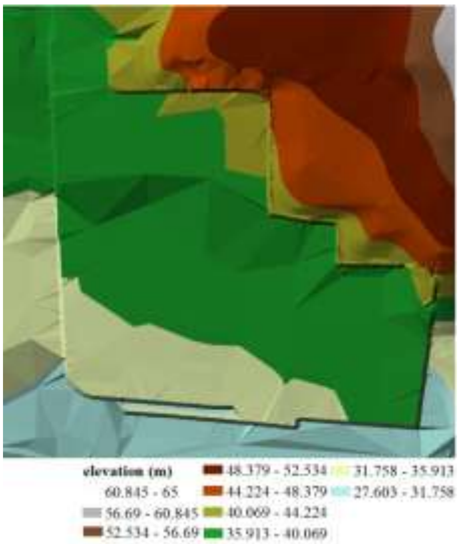
(e) conventional method in terrain-C



(f) new method in terrain-C



(g) conventional method in terrain-D



(h) new method in terrain-D

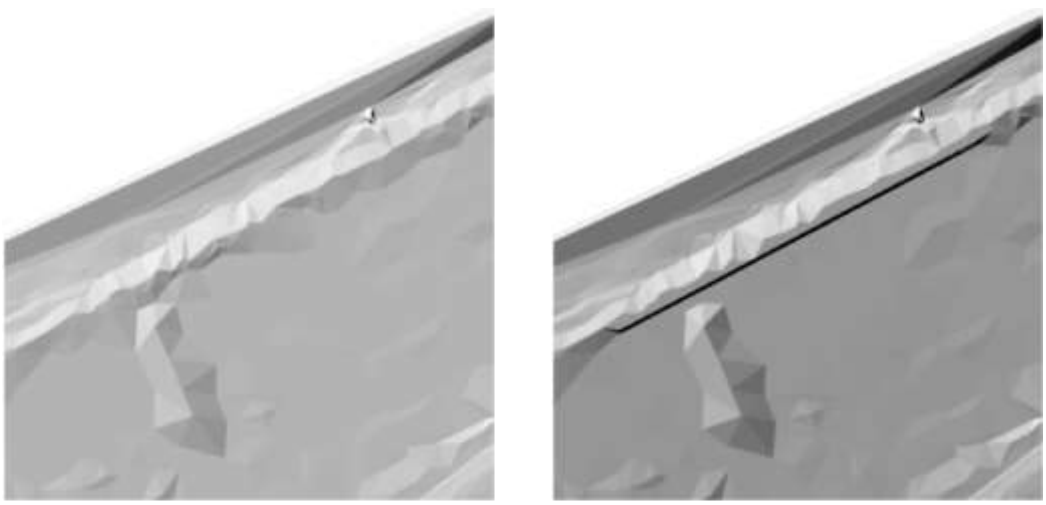
Fig. 4 TINs from the conventional method and the new method

4.2 Relief map analysis

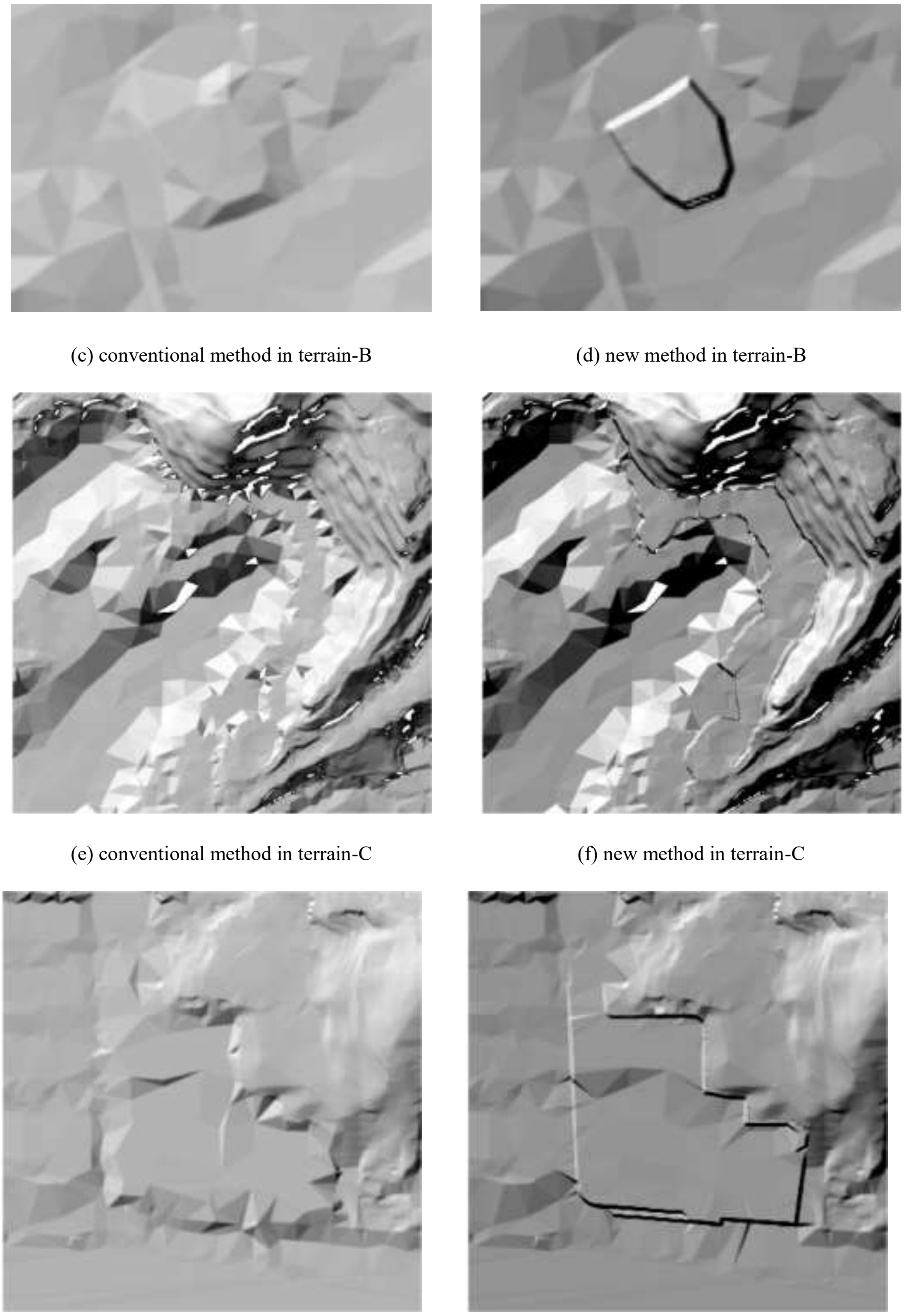
A relief map is essentially a grayscale image that ranges from 0 to 255 that is produced by computing the neighborhood height value given a light source that illuminates the surface from a

certain angle and height. A relief map can be computed by ArcGIS based on a DEM. The relief map clearly reveals the three-dimensional undulation of the terrain when the direction angle and height angle are 315 degrees and 45 degrees, respectively. Thus, relief maps are often used to analyze the morphological features of DEMs.

For the four selected terrains in this study, Figure 5 shows the relief maps produced from DEMs of the conventional and new methods. There is severe distortion in the terrain expression at the feature line of the DEM constructed by conventional methods. The terrain at the feature line is formed as an irregular slope (Terrain-A), and some special terrain highlighted by the topographic feature line is not effectively expressed (Terrain-B). In the area with complex terrain, abnormally zigzag ground is produced on both sides of the feature line shape (Terrain-C and Terrain-D). However, the above problems can be solved by using the TIN construction method proposed in this study. The surface elevation at the feature line changes prominently from high to low (Terrain-A), special terrain can be clearly expressed (Terrain-B), and the difference in terrain on both sides of the topographic feature line can be well expressed in complex terrain areas (Terrain-C and Terrain-D).



(a) conventional method in terrain-A (b) new method in terrain-A



(c) conventional method in terrain-B

(d) new method in terrain-B

(e) conventional method in terrain-C

(f) new method in terrain-C

(g) conventional method in terrain-D

(h) new method in terrain-D

Fig. 5 Relief maps from the conventional method and the new method

4.3 Elevation analysis of topographic feature lines

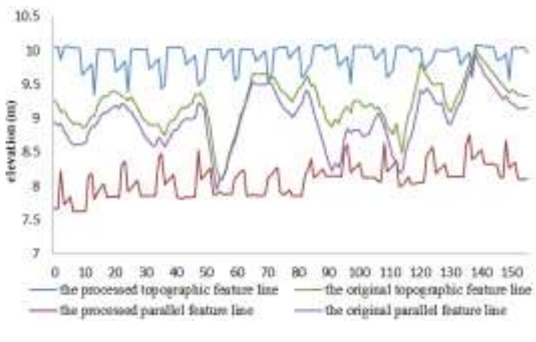
In parts 4.1 and 4.2, the TIN constructed by different methods and the relief maps generated by different methods are compared and analyzed. The advantages of this method in the expression of surface morphology can be seen from the view of vision, but the difference in topographic feature line elevation change is not described quantitatively. In this section, we compare and analyze the elevation changes of different DEM construction results to illustrate the difference between the DEM results constructed by the new method and the traditional method.

First, vertices are inserted into the topographic feature lines and the parallel feature lines according to the specified step size parameter, which is set to be consistent with the grid size of the DEM in this study. Then, the height values of the grids that contain vertices from DEMs constructed by the traditional method and the new method are assigned to the corresponding vertices; finally, the elevation changes of each topographic feature line and parallel feature line are drawn in the form of a curve, in which the ordinate represents the height value of the vertices in the feature lines and the abscissa represents the distance from the present vertex to the first vertex, as shown in Figure 6.

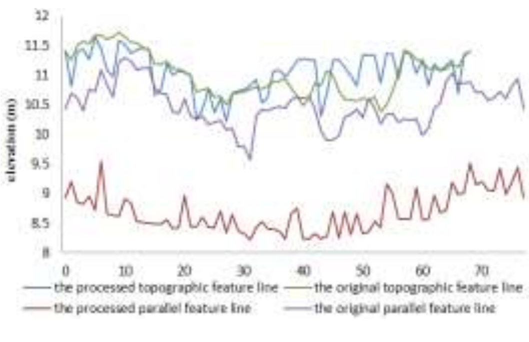
The figure shows that the change trend of the elevation curve of the topographic feature line and the parallel feature line obtained from DEMs constructed by the conventional method is essentially consistent; there is a certain height difference between the two lines, but it is not significant. The reason is that the altimetric points on both sides of the feature lines are used to estimate the height value of the vertices in the feature lines in the process of the conventional method, and the result is that the elevation difference between the topographic feature line and the parallel feature line is limited to some extent. For the elevation change curves of the two lines obtained from the DEM constructed by the new method, there is an obvious height difference between the two

lines, and the change trend of the two lines is different. This is because the altimetric points on one side are used for the estimation of the height value of vertices in the topographic feature line and parallel feature line during the process of the new method and because the height value and the distribution of the points on the two sides are both different.

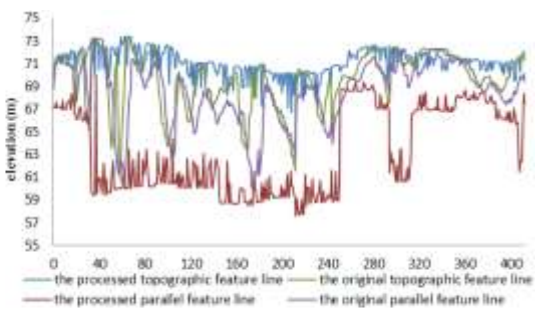
The figure also shows that the elevation change curves of topographic feature lines and their parallel feature lines obtained from DEM construction based on the traditional method are distributed essentially in the middle of the two elevation change curves obtained from DEM construction based on the new method. This phenomenon is easy to understand because the traditional method uses altimetric points on both sides when estimating the height values of the vertices in the feature lines, so the side with the higher height value is pulled down, and the side with the lower height value is raised; this information can also be applied to explain the difference of DEM morphology observed in 4.1 and 4.2. In addition, in the area with complex terrain (Terrain-C), the elevation change curves of two lines obtained from DEM construction based on the traditional method show violent shaking phenomena, which is due to the phenomenon of concave terrain crossing the topographic feature line at the corresponding position, which has been analyzed in Section 4.1.



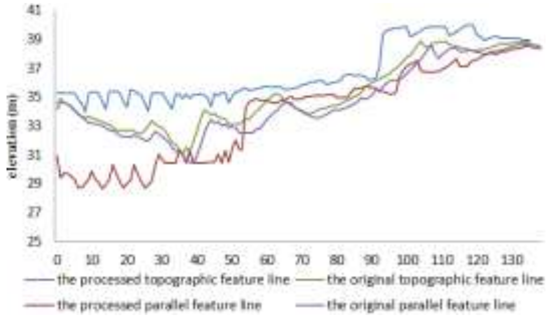
(a) Terrain-A



(b) Terrain-B



(c) Terrain-C



(d) Terrain-D

Fig. 6 Elevation variation of topographic feature line and parallel feature line before and after processing

4.4 Height accuracy analysis

The above section focuses on the analysis of the advantages of the DEM modeling method proposed in this study compared with conventional methods from the perspective of morphological accuracy. Although the advantages of the method proposed in this study are obvious, the change in morphology clearly comes from the change in elevation. Therefore, this part of the paper compares and analyzes the advantages of the DEM modeling method proposed in this study from the perspective of height accuracy.

It should be emphasized that this study is aimed at optimizing the integration of topographic feature lines in DEM modeling. Therefore, the differences between the DEM modeling results and traditional modeling results in this study are mainly distributed on both sides of topographic feature lines. Therefore, in this paper, we select only the elevation verification points from both sides of the topographic feature line (set as 10 m in this paper) to evaluate and analyze the accuracy of the results of the two modeling methods.

The indicators employed to verify the height accuracy were the mean error and root mean square error. The mean error reflects the averaged difference between the DEM values and the height

values of the verification points, which can reflect the error distribution. The root mean square error reflects the dispersion of a data set. The error indicator can be calculated as follows:

$$MAE = \frac{1}{n}\sum \left| O(x, y) - S(x, y) \right|, (x, y) \in R^2 \quad (3)$$

$$RMSE = \sqrt{\frac{\sum \left(O(x, y) - S(x, y) \right)^2}{n-1}}, (x, y) \in R^2 \, (2) \quad (4)$$

where MAE represents the average error, $RMSE$ represents the standard deviation, $\mathrm{O}(x, y)$ represents the observed height value at the verification point, $\mathrm{S}(x, y)$ represents the height value on the DEM generated by different methods at the verification point, (x, y) represents the location coordinates of the point, and R^2 is the real number field.

For the four small experimental areas selected in this study, three error indexes are calculated, as are the error indexes of the whole experimental area. The results are shown in Table 2.

Tab. 2 Error statistics of different modeling methods

	MAX_E		MAE		RMSE	
	Traditional	New	Traditional	New	Traditional	New
Terrain-A	1.40	0.99	0.82	0.40	0.56	0.41
Terrain-B	1.70	0.53	0.84	0.24	0.71	0.21
Terrain-C	8.30	3.39	0.87	0.30	2.05	0.79
Terrain-D	3.23	1.86	0.15	0.14	0.39	0.26
Whole	8.30	3.39	0.28	0.17	0.90	0.38

The above three error indicators for the four selected discontinuous terrain regions show that the construction results of this study are better than those of the traditional construction methods.

For example, for the max_ E index, the traditional method results are more than 1 m, even when the complex terrain experimental Terrain-C reaches 8.30 m. The MAX_E of the new method decreases significantly. For flat terrain test Terrain-A and Terrain-B, the MAX_E value decreases to less than 1 m, and only in complex terrain test Terrain-C and Terrain-D is the value more than 1 m. For the MAE index, only in Terrain-D is the precision advantage of this method not obvious, and the MAE values of other experimental areas are reduced by more than 50% of the corresponding error value of the traditional method; for the RMSE index, the construction result of this method is also greatly improved over the traditional results. On the whole, compared with the traditional method, the DEM constructed by the method proposed in this paper significantly decreases the MAX_E, decreases the MAE by 0.11 m, and decreases the RMSE by nearly 60%. It can be concluded that this method is superior to the traditional method in height accuracy.

5 Conclusion

Human activities have created various forms of discontinuous topography, and traditional DEM construction methods have severe distortion problems in these discontinuous topographies. Unfortunately, the current methods do not make full use of the topographic feature lines in DEM construction of discontinuous topography. To solve this problem, this paper proposes a method that can effectively integrate topographic feature lines in the process of TIN construction, which can ensure the effective expression of morphological features of discontinuous terrain. The main advantages of the proposed method are listed as follows:

(1) In areas with discontinuous topography, this research generates a parallel feature line based on the existing topographic feature line and then calculates the height value of the vertices in the two feature lines with the known elevation information on one side of the discontinuous terrain to

effectively ensure the accuracy of the elevation on the feature lines.

(2) By generating a parallel line of the topographic feature line, abrupt terrain is expressed as a steep slope, which is in accordance with the morphological characteristics of real discontinuous terrain. Compared with traditional construction methods, the constructed DEM has obvious improvements in both shape accuracy and height accuracy.

(3) The method proposed in this paper is designed based on the traditional DEM construction process. By skillfully processing the topographic feature lines, DEM optimization can be realized without changing the DEM data structure and the core algorithm of DEM generation. The process is simple and easy to implement, which makes the method very easy to compatible with existing GIS software and easy to apply in the GIS field.

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Figures

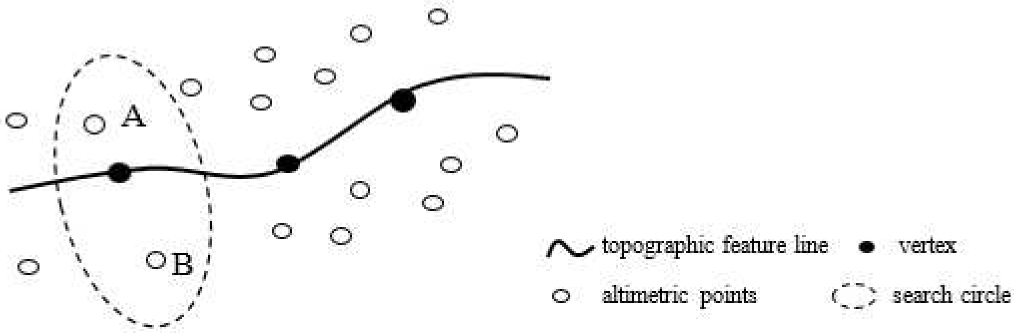

Figure 1

Height calculation of vertices in the topographic feature line

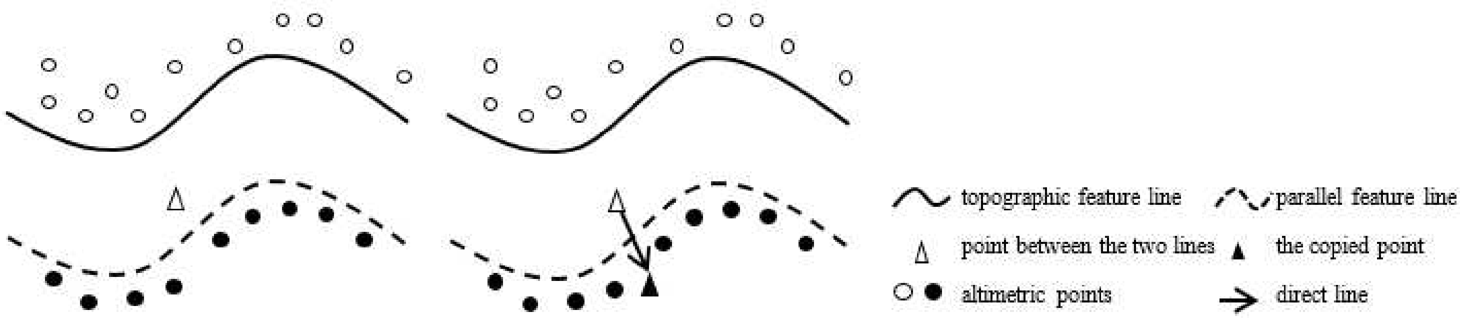

Figure 2

Spatial relationship between topographic feature line and parallel feature line

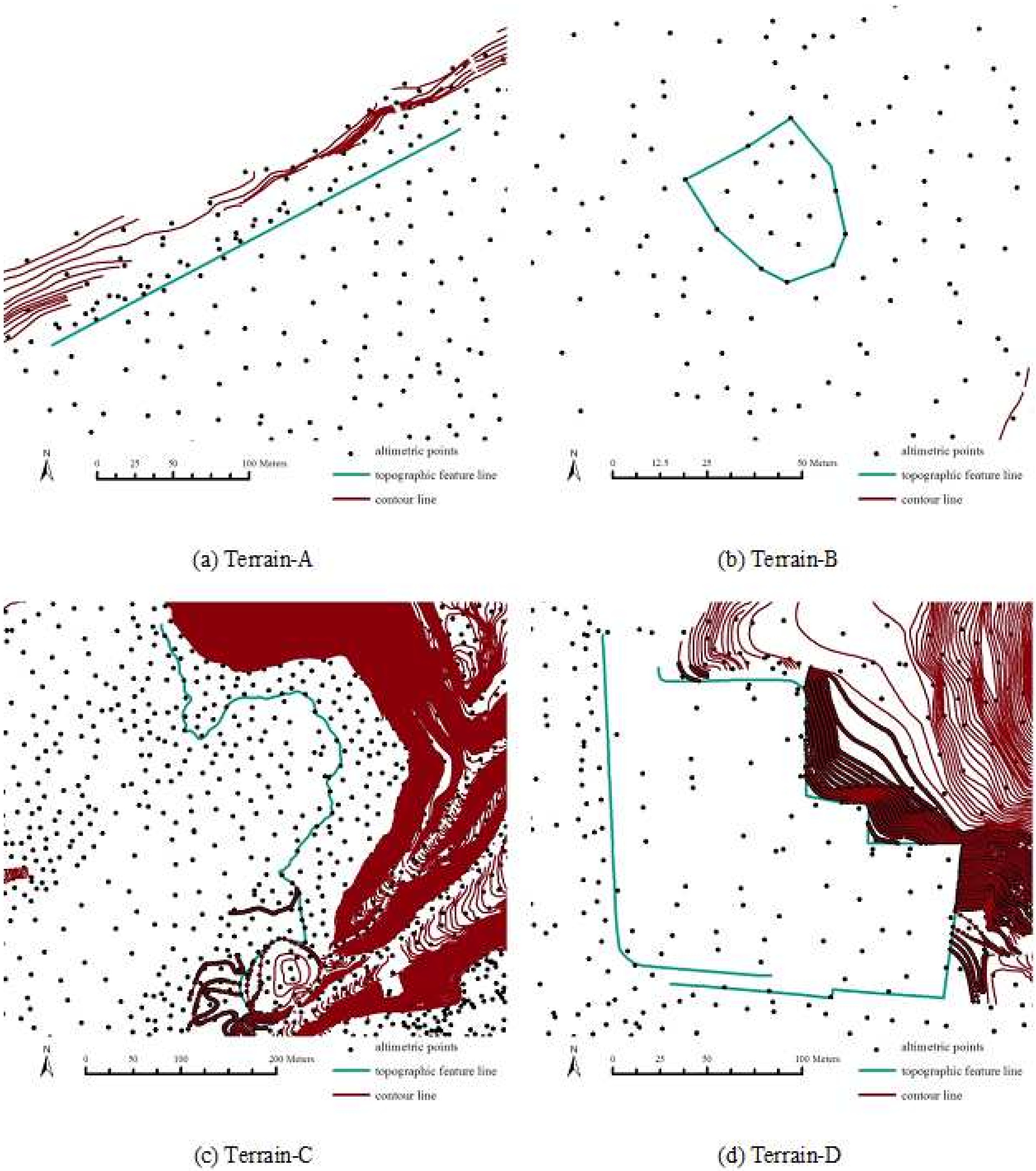

Figure 3

Topographic map of the study area

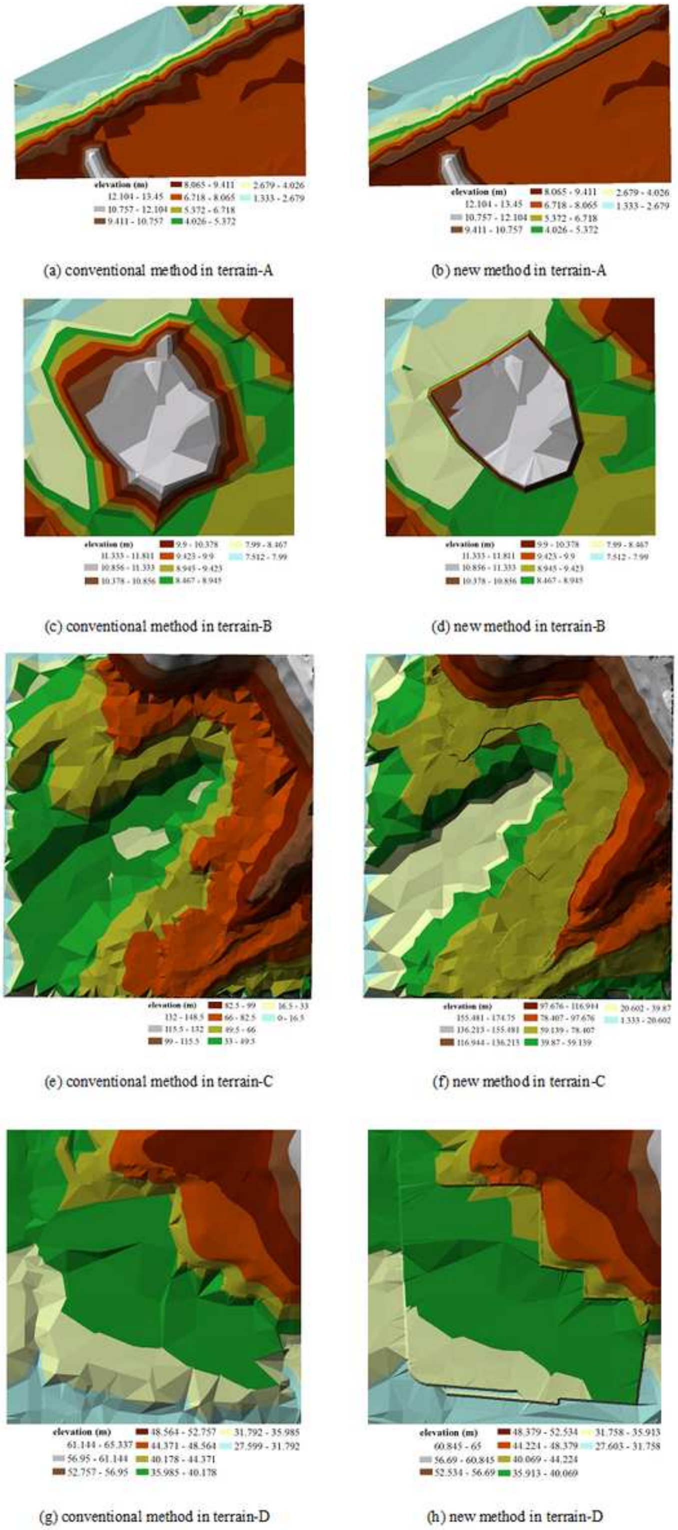

Figure 4

TINs from the conventional method and the new method

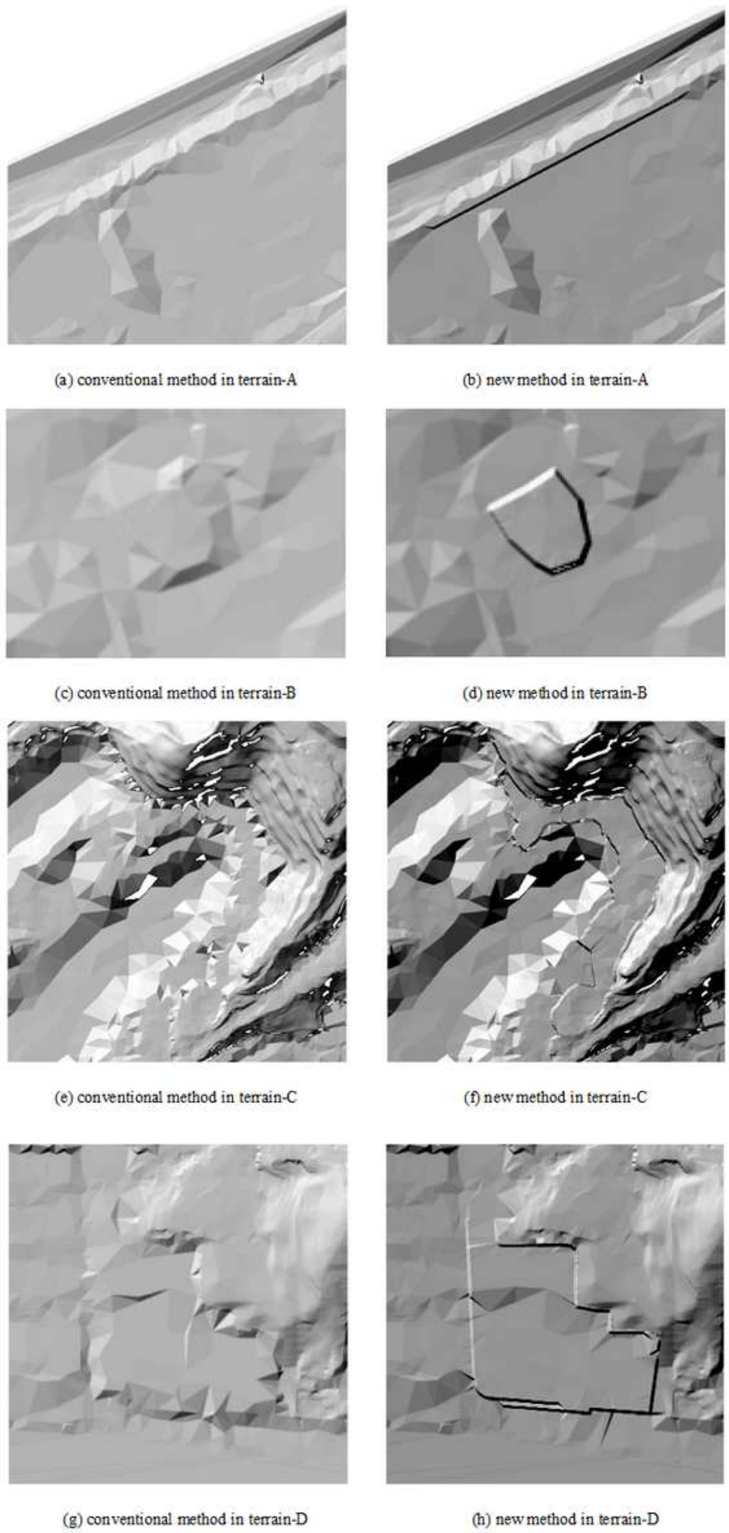

Figure 5

Relief maps from the conventional method and the new method

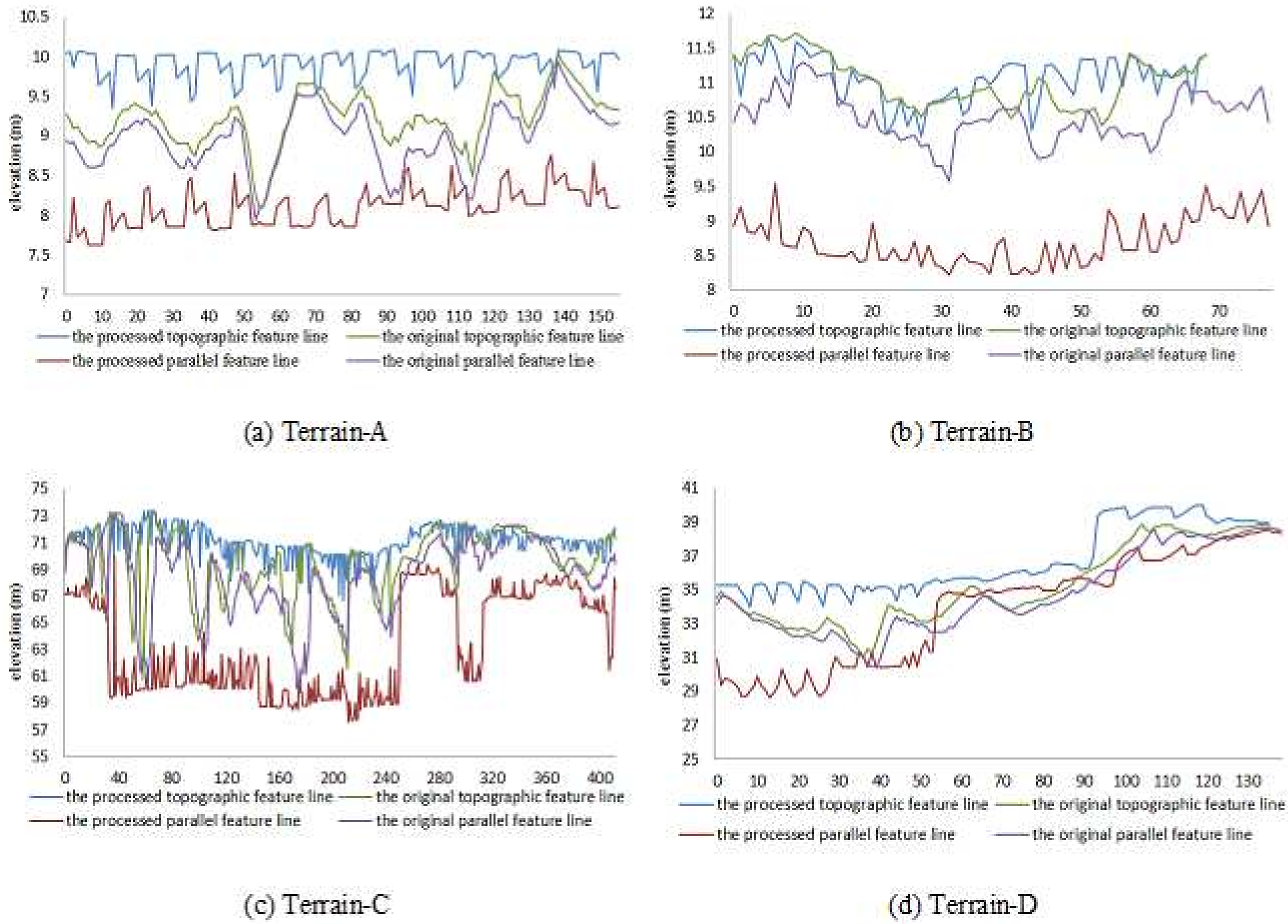

Figure 6

Elevation variation of topographic feature line and parallel feature line before and after processing