3D DP Improved Algorithm Based on Bending Hierarchy Structure Identification

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Abstract. 3D Douglas-Peucker (DP) algorithm is an effective 3D discrete point data synthesis algorithm. In view of over-synthesis of compound bending during simplification of 3D DP algorithm with additional bending adjustment index, this paper designs a bending hierarchical structured algorithm to improve the original algorithm. Bending convexity threshold is introduced to merge the bending operation, curve skeletons with different scales are selected through statistics of bending height distribution. Bending adjustment index on different hierarchies of bending skeleton is calculated for synchronous synthesis between line features and DEM. The experimental results show that the structuring process well retains the original details of the curve, clearly presents the overall curve trend with obvious simplification effect, thus solving the problem of over-synthesis of compound bending, so that the curve displays different bending hierarchy structures. The simplification result demonstrates completeness of geographical significance and similarity between the graphics before and after the simplification.

Keywords. 3D DP algorithm, bending hierarchy, bending structuring

1. Introduction

3D Douglas-Peucker algorithm is an effective DEM automatic synthesis algorithm based on 3D discrete point data format. It can automatically delete insignificant landforms failing to achieve the threshold, thus well maintaining the main landform features of the original DEM, which is applied to DEM synthesis, landform feature extraction, real-time display, 3D discrete point set extraction [1-4]. Dou Shiqing et al. introduced bending adjustment index B in 3D DP algorithm. That is, area coefficient e, bending degree f, and bending adjustment constant C are used to calculate the pseudo-point-to-plane distance from the midpoint to the base surface in 3D DP algorithm, so that bending geometrical feature is incorporated into the algorithm threshold determination process. In synchronous simplification of river network lines and DEM using 3D DP algorithm, the main geometric form and terrain features of the curve are retained at the same time [5]. However, in 3D DP algorithm simplification based on bending adjustment index, the bending adjustment index takes basic bending as the assignment unit. Some basic bending has small shapes. In the automatic synthesis, the points on basic bending are all deleted because of failure to achieve the algorithm threshold, resulting in over-synthesis of the compound bending, which affects
simplification quality [6], as shown in Figure 1 (the red line represents the river before simplification, and the blue line represents the river after simplification by 3D DP algorithm based on bending adjustment index).

Figure 1. Over comprehensive sketch map.

In response to this problem, this paper designs a bending hierarchical structured algorithm, which aims to retain the original bending characteristics of the curve, and extract compound bending as skeleton form of different hierarchies, so that bending structure of the 3D river element on the 2D plane can be saved in the form of compounding bending set. Moreover, bending structuring is applied to improved 3D DP algorithm, so that the overall bending shape of the curve will not be affected by over-synthesis of small bending after 3D DP simplification. In this way, the simplified linear elements retain relatively intact characteristic skeleton in the plains with relatively small terrain undulation, thus conforming to the original landform features.

2. Principle of curve hierarchical structuring

2.1. Principle of curve hierarchy
Hierarchy here refers to gradual morphology change exhibited in simplification results of different thresholds. Under different thresholds, geographic element features expressed by bending hierarchical division are different.

Figure 2. Gradation shown.

As shown in Figure 2, in example with compound bending AJ, AB, BC, CD, DE, and EF are bending with relatively small heights. Suppose that they meet the conditions for deletion, but FG and HI do not, then the divided curve mainly exhibits bending features of FG and HI. In case of high threshold, FG and HI are also deleted, then compound bending is simplified to AJ polyline through algorithm calculation. However, macrobending formed by AJ polyline fails to achieve the threshold and the curve expresses geometric features of AJ compound curve. If AJ polyline meets the condition for simplification, or its convexity is small, it can be approximated as a straight line, indicating that the compound curve at the current threshold cannot display its geographic features on the curve.
2.2. Curve structuring process

The basic bending is divided by bending division method based on inflection point [7-12]. To distinguish geometric shape of the basic bending, this paper introduces bending height and bending convexity as the screening conditions. In basic bending, bending height can be expressed as the maximum distance from bending point to the baseline, as shown in Figure 3. \( p_1P_{\text{end}} \) is the bending baseline, and \( d \) is the basic bending height.

![Figure 3. The bend height map.](image)

The traditional curvature \( f \) is decided based on the ratio of bending length to baseline. In compound bending determination, bending length will be lengthened by the small bending in the compound bending, and spatial significance of the bending shape cannot be accurately interpreted. Therefore, this paper introduces bending convexity to describe morphological convexity of the bending, and its value is a positive number greater than 0 (when it is equal to 0, it is a straight line segment). The convexity is the ratio of bending height to baseline length, which is set to \( W \) and defined as:

\[
W = \frac{d}{P_1P_{\text{end}}}
\]

(1) Bending height \( d \) is solved by traversing each bending. An appropriate threshold \( H \) is selected based on empirical value from the statistical experiment to classify the bending. If \( d > H \), all points on the bending are stored as a class of points, and each bending number and bending peak number are recorded. Otherwise, the two ends of the bending baseline are recorded as second-class points, and the points between the two ends of the bending are deleted, as shown in Figure 4.

![Figure 4. Bending point classification.](image)

(2) After the bending height threshold is determined for all the bending, a complete set of second-class points is obtained. The points are merged and connected into a new curve according to the sequence number. All the bending is traversed for further division. Characteristic bending array is saved and points on the same bending are assigned with the same bending number;

(3) Input the threshold of bending convexity \( W \), merge the non-characteristic bending from the characteristic bending array backwards to form basic bending via bending peak of concentrated characteristic bending point and the two adjacent second-class points. If the convexity degree \( W \) is smaller than the input threshold, view it as an insignificant line segment of curve feature and merge it with characteristic bending of the peak into the same bending array. Loop this process to determine backwards until the next characteristic bending stops determination. Otherwise, stop determination as shown in Figure 5.
(4) Assign bending sequence number to each first-class point array. Assign a negative value to all points of the same field in the second-class point set. Output the data to derive a first-level result. At this time, if the main bending geometric features are saved, the points in the original data form a bending "skeleton";

(5) Bending heights of all basic bending in 1 are calculated to determine multiple representative thresholds according to size range of d value. Use different thresholds to synchronize the data so that point set after bending division at different hierarchies is obtained.

3. Threshold selection experiment

The experimental data used herein are river network data and DEM data within a range of 23,000 square kilometers from Luanping County, Hebei Province, as shown in Figure 6.

Select one representative curve for hierarchical structure division of all the curve points it contains. The bold part of the blue line in Figure 7 shows linear data for the structured algorithm and hierarchy extraction results.

3.1. Selection of bending height threshold

The selected experimental data is subject to bending division. 202 basic bending are selected as samples, and each basic bending of the curve is traversed to find the bending height d. Then, calculate bending height distribution of the curve, as shown in Figure 8.
The statistical results show that the bending heights on the curve are mainly distributed in the range of 0-1550, accounting for 80.7% of all bendings. Where, 43 bendings have a height less than 350, accounting for 21.2% of all bendings; 81 bendings have a height less than 550, accounting for 40.1% of the total, and bendings with a height less than 850 account for 59.4% of the total, as shown in Figure 9. Obvious stepped distribution characteristics are shown in number. It can be considered that in the case of natural distribution, bending height has a linear relationship with ratio of bending of corresponding height in all bending. Thus, according to the concept of hierarchy, this paper divides the curve bending into four hierarchies, and selects 350, 550, 850, and 1550 as the bending height determination thresholds to structure the river data.

3.2. Selection of bending convexity threshold
The bending convexity formed by the experimental points has a minimum value of 0.000205667 and a maximum value of 3.557023651, with a big gap in order of magnitudes. Considering the error in bending division by inflection point, individual extreme values are deleted. Statistical information shows that bendings with convexity between 0-0.01 account for 18% of the total, that with convexity in the range of 0.01-0.1 account for 37.1% of the total, and that with convexity greater than 0.1 account for 44.9% of the total, as shown in Figure 10. According to the principle of structured algorithm, setting of convexity threshold should make the point set involved in the determination unable to form a bending with obvious features, so the selected threshold should be smaller than most convexity values. This paper uses 0.1 as the bending convexity threshold.
3.3. Analysis of structured algorithm results

For this experimental line element, this paper adopts four bending height thresholds 350, 550, 850, 1550 and bending convexity threshold 0.1 in the hierarchical structured algorithm to filter the basic bending. Curve results as different hierarchies are then obtained by dividing the characteristic skeleton bending. The results after structuring of different hierarchies are shown in Figure 11.

The bending feature points are retained under four bending height thresholds of 350, 550, 850, 1550 and the number of bending divisions are counted, as shown in Table 1. When bending height threshold is 0, data is curve data without structured algorithm, which is compared with the other four sets of data as a reference.
Table 1. Different threshold structured graphic elements contrast.

| Bending height threshold | Number of bending points after structuring | Bending merger rate | Number of points after structuring | Retention rate | Number of second-class points |
|--------------------------|------------------------------------------|--------------------|-----------------------------------|----------------|-----------------------------|
| 0                        | 171                                      | 0%                 | 303                               | 100%           | 0                           |
| 350                      | 54                                       | 68.4%              | 257                               | 84.8%          | 10                          |
| 550                      | 42                                       | 75.4%              | 238                               | 78.5%          | 18                          |
| 850                      | 27                                       | 84.2%              | 195                               | 64.3%          | 32                          |
| 1550                     | 19                                       | 88.9%              | 162                               | 53.5%          | 46                          |

By analyzing bending structuring results of these four hierarchies, we can see:

1. When the bending height threshold is selected as 350, that is, basic bending accounting for about 20% of the total bending in the original linear data is synthesized, for curve skeleton composed of second-class points and non-synthesized characteristic bending, basic bending has a merger rate of 68.4%. That is, 68.4% of the curve bending are structured and merged into a compound bending. 84.8% points on the curve are retained, so the retention rate is relatively high. Under this threshold, relatively simple compound bending with smaller scale is obtained by structured algorithm.

2. Under bending height threshold of 550, 40% bending on the curve is synthesized, with merger rate at 75.4%. At this time, bigger compound bending on the curve reveals its skeleton because the basic bending thereof is replaced by the baseline end point. The curve skeleton at this scale retains most of the bending.

3. Under bending height threshold of 850, the bending merger rate on the curve is 84.2%. At this time, bigger bending can retain the points thereof and merge the second-class points on both sides, and 35.7% points on the curve are synthesized.

4. Under bending height threshold of 1550, only individual bending can be retained. At this time, the curve is highly skeletonized, only revealing its direction, but geographical features of the details cannot be displayed.

4. 3D DP improvement research and experiment based on hierarchical structured algorithm

The principle of 3D DP improved algorithm is as follows:

1. First, construct river system tree and select the number of rivers based on the selected river network data, extract the discrete points of the river network, and assign value to elevation of the river network points through DEM elevation data fitting;

2. Under a certain threshold of 3D DP algorithm, extract curve skeletons at different hierarchies from river network lines according to different thresholds of bending heights. Select the most suitable skeleton result of a certain hierarchy as the starting data for algorithm simplification according to human eye judgment and simplification requirements.

3. Bending adjustment index is calculated based on compound bending on the skeleton. Bending width, length, and area are calculated from compound bending after corresponding hierarchical structuring. Finally, the processed 3D river network points and DEM points are used as original data for determination of the pseudo-point-to-plane distance to simplify the algorithm.

To differentiate the experimental results, skeleton structured under height threshold of 350 and 850 is selected for 3D DP simplification of the experimental data. The comparison data has threshold 800m, the bending adjustment index is \( C_1=3 \) in plain areas, and \( C_2=C_3= \) in mountainous areas. The simplified result is shown in Figure 12 and Figure 13.
Figure 12. Structured algorithm H threshold 350, W threshold 0.1 contrast figure.

Figure 13. Contrast figure of H threshold for 850, W threshold for 0.1. Statistics is made on the river network data synthesis results, bending retention after simplification and point retention rate after structuring with 350 and 850 as the threshold, as shown in Table 2.
Table 2. Result of the experiment data statistics.

| simplification threshold | Structured algorithm simplification threshold | Number of bending after simplification | Bending retention ratio | Number of points after simplification | Point retention ratio | Running time (s) |
|--------------------------|---------------------------------------------|---------------------------------------|------------------------|--------------------------------------|----------------------|------------------|
| 800                      | 0                                           | 659                                   | 89.2%                  | 1511                                 | 0.91                 | 0.85             |
| C1=3,C2=C3=1             | 350                                         | 492                                   | 66.3%                  | 987                                  | 0.59                 | 0.89             |
|                          | 850                                         | 337                                   | 45.4%                  | 807                                  | 0.49                 | 0.88             |

Analysis of the simplification results of these two hierarchies reveals that:
1. Under determined view size, detailed geographic features contained in the hierarchical skeleton are more comprehensive with small compound bending scale and high original data retention rate when smaller structured threshold value is selected. Under higher hierarchy, compound bending has bigger spatial scale and lower retention rate after simplification. Choice of hierarchy under a fixed view should be determined according to the simplification requirements.
2. For river under natural distribution, size distribution of bending height of all curves can be approximated as a linear distribution, but according to different simplification requirements, a certain function can be selected to choose thresholds of different hierarchies. For instance: the minimum threshold can be set as the median, mean value, etc. of the bending height.
3. Threshold selection of 3D DP algorithm is based on elevation. In structured algorithm, threshold is selected based on bending scale at the 2D hierarchy. Therefore, it is difficult to establish an accurate mathematical connection between 3D DP and structured algorithm threshold. Comprehensive handling of practical issues requires manual experiments or automatic control based on artificial neural networks in threshold selection.

5. Conclusion
This paper introduces bending hierarchical structured algorithm to improve the 3D DP algorithm with additional bending adjustment index. Through experimental analysis, the following conclusions are drawn:
1. In structured algorithm, under small bending height threshold, the retention rate of the curve points is high, and compound bending with small scale is possible without over-synthesis, so that it is more adapted to human eye identification of bending after synthesis. Different hierarchies of curve bending can be reasonably differentiated via selection of structural algorithm thresholds, and different amounts of information are retained under simplification at different hierarchies.
2. In 3D DP improvement experiment based on structured bending hierarchy, the structuring process changes the assignment object of the bending adjustment index from basic bending to compound bending, which solves the problem of over-synthesis in the simplification process and makes the simplified result and bending structure more in line with geographic characteristics of the curve. Different bending height thresholds display curve characteristics at different scales.

In the current experiment, relationship between bending adjustment index and hierarchical structured algorithm threshold cannot be indicated via a definite functional relationship. Quality determination of the comprehensive effect mainly depends on human eye observation, which is subjective. These problems demand more in-depth subsequent researches.

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