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Fractal Characteristics of Landslide Slope Variation-a Case Study of Lanzhou

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Abstract: ***This study investigates the spatial distribution characteristics of landslides using fractal theory. Based on landslide distribution patterns and regional geological conditions in Lanzhou City, we employ variable-dimensional fractal methods to analyze both constant and variable-dimensional fractal features. The results demonstrate that Lanzhou's landslide systems exhibit higher fractal dimensions in variable-dimensional analysis. The fractal dimension value serves as an indicator of correlation strength between landslides and related factors: higher values indicate stronger correlations, suggesting these factors play more significant roles in landslide occurrence and development. Conversely, lower values suggest relatively weaker influences. For the study area, the correlation ranking of landslide and its influencing factors is slope> elevation> lithology. The fractal dimension obtained by the study can help researchers to better understand the spatial distribution law of landslides in Lanzhou, reveal the complexity and fractal characteristics of landslides in Lanzhou, and thus deeply understand the evolution process and spatial distribution law of landslides.***

Keywords: Landslide, Variable dimensional fractal, Distribution characteristics, Geologic hazard**.**

1. Introduction

Landslides, a widespread and frequent geological hazard, significantly impact human life. With social development, human factors have become primary triggers. Recent years have witnessed increasingly severe landslide disasters, making research on this phenomenon both crucial and urgent. Spatial distribution studies of landslides represent a vital research direction.

Landslide distribution may appear random, yet it actually exhibits regional patterns and recurrence. Investigating its spatial distribution helps uncover underlying characteristics, and fractal theory provides an ideal framework for addressing such challenges. Currently, fractal theory has been extensively applied across multiple disciplines, standing as a cutting-edge international research field. Some scholars predict it may become the mainstream approach in geology, highlighting its significant academic value. The core concept of fractal theory is "self-similarity" – the statistical resemblance between local and global scales. Applying fractal theory to landslide analysis reveals intrinsic spatial distribution patterns. This methodology enables researchers to examine the whole through local features, identify general principles from specific cases, and ultimately reveal fractal phenomena and characteristics of landslides while investigating their mechanisms. Building on fractal theory and considering complex geological factors, this study investigates their influence on the spatial distribution patterns of landslides [1-8].

2. Study Area and Data Source

2.1 Overview of the Study Area

This study focuses on Lanzhou City in Gansu Province, situated within the Tianshui-Lanzhou seismic belt—a region characterized by frequent landslides and complex environmental conditions that form a nonlinear system, making conventional research methods challenging. Lanzhou lies at the convergence of the Loess Plateau and Qinghai-Tibet Plateau, featuring a terrain that slopes southward. The northwest area, comprising a small portion of the Qinghai-Tibet Plateau, reaches approximately 2,000 meters in elevation. The southeastern region, part of the Longxi Loess Plateau in the mountainous sub-region, exhibits complex geological structures and significant topographical variations. As the upper reaches of the Yellow River flow from southwest to northeast across the entire territory, cutting through mountain ridges, Lanzhou has developed a portion of the Yellow River valley.

Figure 1: Satellite map of the study area

2.2 Data Source

The landslide data is sourced from the official document "Lanzhou City Geological Disaster Prevention Plan (2007-2020)" issued by the Lanzhou Municipal People's Government. According to official statistics, there were 519 geological disaster sites involving landslides, collapses, and unstable slopes in Lanzhou City between 2007 and 2020, with

Table 1: Detailed Distribution Table of Geological Disasters in the Study Area

area \ disaster species	Landslide	Collapse	Unstable slope	Total	proportion /%
Chengguan District	32	8	67	107	20.62
Qilihe District	31	4	31	66	12.72
Anning District	3	2	10	15	2.89
Xigu District	12	6	12	30	5.78
Honggu District	17	8	14	39	7.51
Gaolan County	7	0	26	33	6.36
Yuzhong County	25	22	0	47	9.05
Yongdeng County	54	52	76	182	35.07
total, summation	181	102	236	519	100

181 landslides, 102 collapses, and 236 unstable slopes. The distribution is as follows: Chengguan District (107 sites, 20.62% of total); Qilihe District (66 sites, 12.72%); Anning District (15 sites, 2.89%); Xigu District (30 sites, 5.78%); Honggu District (39 sites, 7.51%); Gaolan County (33 sites, 6.36%); Yuzhong County (47 sites, 9.06%); and Yongdeng County (182 sites, 35.07%). Table 1 is the detailed classification table of geological disasters in the study area.

The landslide data from Table 1 were processed using ArcGIS and other software, resulting in Figure 2 (Disaster Landslide Distribution Map in the Study Area).

Figure 2: Disaster distribution map of the study area

Since variable-dimensional fractals require more precise landslide data, the data for variable-dimensional fractals was compiled by cross-referencing public records with regional academic papers. In practical applications, data should be processed appropriately to minimize errors [9-30].

3. Fractal Model Method

Fractal theory stems from fractional dimensions. In traditional geometry, dimensions are integers (1D for line segment, 2D for plane, 3D for cube), but fractional dimensions, non - integers, describe fractals' self - similarity and can characterize the relationship between a fractal's local and global properties.

As Mandelbrot said, fractals are everywhere. The study of fractal theory is significant due to self - similarity, providing an effective way to analyze complex phenomena. Since its start, it has been widely used in disciplines like computer science, geology, and finance for data analysis with good results. Its advantage lies in modifying dimensional definition to improve object characterization precision. This characteristic allows diverse dimensional measurement methods, with the box dimension method and its derivative cumulative sum analysis being common in this study [31].

A constant dimensional fractal is defined as one where the fractal dimension N(r) remains constant regardless of the characteristic scale r, with no functional relationship between them. In landslide distribution statistics, many parameters fall under this category. Analyzing constant dimensional fractals helps us better understand the underlying patterns in landslide distribution. Therefore, it is essential to employ this approach in studying landslide-related parameters.

In fractals, N(r) is not a constant but a function of the characteristic scale r. When N(r) varies with r, it is called a fractal of variable dimension.

Conventional fractals have significant limitations, being applicable only when the fractal dimension is less than or near two and the phase space dimensionality remains low. However, landslide spatial distribution analysis requires more complex spatial dimensions than simple 2D studies, making conventional fractals often inadequate. This necessitates the application of variable-dimensional fractals. When employing variable-dimensional fractals, the box dimension method becomes insufficient, as it becomes challenging to plot the relationship between landslide influence factors and volume using box dimension charts. Even when such charts are created, the N(r) curve typically fails to conform to a linear pattern. To address this, Fu Yuhua et al. expanded the box dimension method for marine environmental data prediction, proposing a transformed fractal framework – a novel variable-dimensional analysis approach called the Cumulative Sum Variable-Dimension Analysis [32].

The cumulative sum and fractal dimension analysis method is derived from the relationship between N(r) and r. To establish this methodology, we treat the fractal dimension D=F(r) as a functional relationship. By applying cumulative sum transformations of varying orders to data points, we can construct fractal dimension models at different orders. Through comparative evaluation of model performance across orders, we select the most effective transformation and determine its corresponding fractal parameters. The procedure is as follows:

(1) Identify the original data points (Ni, ri), sort them in descending order, form an array, and plot a double-logarithmic graph (e.g., {Ni} = {N1, N2, N3,...}). Connect adjacent points with lines on the graph, calculate the slope of each line, and according to the definition of the box dimension method, the reciprocal of the slope yields the

fractal dimension D. Alternatively, plotting logNi versus log(1/ri) directly yields the slope D.

(2) Construct the cumulative sum of each order. The definition of the first-order cumulative sum transformation is as follows:

$$\{S1i\}=\{N1, N1+N2, N1+N2+N3, \ldots\ldots\} \quad (1)$$

$$\{S2i\}=\{S11, S11+S12, S11+S12+S13, \ldots\ldots\} \quad (2)$$

$$\{S3i\}=\{S21, S21+S22, S21+S22+S23, \ldots\ldots\} \quad (3)$$

$$\{Sni\} = \{S(n-1)1, S(n-1)1 + S(n-1)2, S(n-1)1 + S(n-1)2 + S(n-1)3, \ldots\ldots\}, \text{ where } i = 1, 2, 3, \ldots\ldots, n. \quad (4)$$

Gradually increase the order until the appropriate order is reached, and plot the cumulative sum curve for each order.

Select the cumulative and transformed curves with good fitting effects to obtain their fractal dimension values.

4. Fractal Characteristics of Landslide

4.1 Fractal Characteristics of Volume and Slope of Landslide

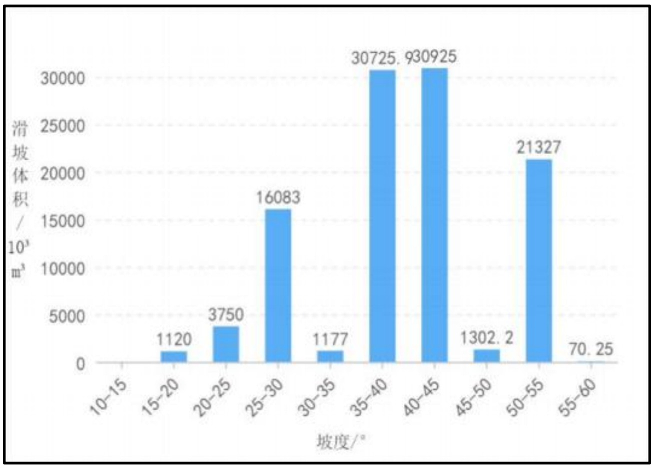

Figure 3: Column chart of landslide volume in different slope ranges

Slope angle is intrinsically linked to landslide development and serves as a critical factor influencing both the formation and evolution of landslides, which in turn affects their occurrence and distribution across different regions. Therefore, studying the fractal characteristics of landslide volume and slope angle is essential. By categorizing slopes into distinct ranges, conducting statistical analysis on the collected data, and applying error correction, we can obtain the landslide volume histogram for various slope ranges as shown in Figure 3.

As shown in Figure 3, the cumulative bar chart of landslide volume shows no distinct trend characteristics with increasing slope angles. This makes the cumulative sum and variable dimension analysis method more effective for linear regression fitting in the double-logarithmic coordinate system. When setting r as the landslide slope range (10-15°), r=1 corresponds to N(r) representing landslide volume in 10^3 m^3. For slopes between 15° and 20°, r=2, and so on, extending up to 60° yields 10 data points. This process generates Statistical Table 2 of landslide slope ranges.

Table 2: Slope range statistics of landslides

r	1	2	3	4	5	6	7	8	9	10
N(r) /103m3	0	1120	3750	16083	1177	30725.9	30925	1302.2	21327	70.25

After processing the data in this table with MATLAB, the cumulative curve in Figure 4 will be obtained.

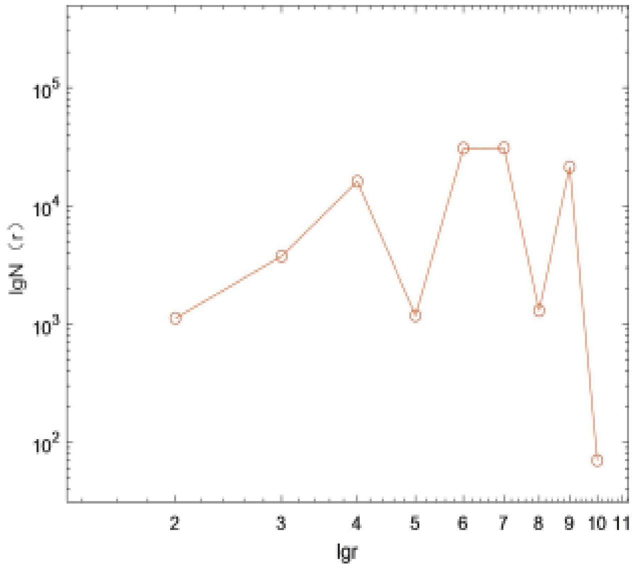

Figure 4: Double-logarithmic curve of landslide volume versus slope

As shown in Figure 4, the hyperbolic relationship between r and N(r) cannot be accurately approximated by a straight line. Therefore, it is more appropriate to employ cumulative sum and dimensional analysis methods. After calculating the first-order cumulative sum S1, second-order cumulative sum S2, and third-order cumulative sum S3, the resulting data are presented in Tables 3,4, and 5.

Similarly, the multi-stage cumulative sum is shown in Figure 5 after processing with MATLAB.

Table 3: Slope range and first-order cumulative landslide volume of landslides

First-order cumulative sum	$S1_1$	$S1_2$	$S1_3$	$S1_4$	$S1_5$	$S1_6$	$S1_7$	$S1_8$	$S1_9$	$S1_{10}$
accumulated value	0	1120	4870	20953	22130	52855.9	83780.9	85083. 1	106410. 1	106480.35

Table 4: Second-order cumulative sum of landslide slope ranges and volumes

Second-order cumulative sum	$S2_1$	$S2_2$	$S2_3$	$S2_4$	$S2_5$	$S2_6$	$S2_7$	$S2_8$	$S2_9$	$S2_{10}$
accumulated value	0	1120	5990	26943	49073	101928.9	185709.8	270792.9	377203	483683.35

Table 5: Third-order cumulative sum of landslide slope ranges and volumes

Third-order cumulative sum	$S3_1$	$S3_2$	$S3_3$	$S3_4$	$S3_5$	$S3_6$	$S3_7$	$S3_8$	$S3_9$	$S3_{10}$
accumulated value	0	1120	7110	34053	83126	185054.9	370764.7	641557.6	1018760.6	1502443.95

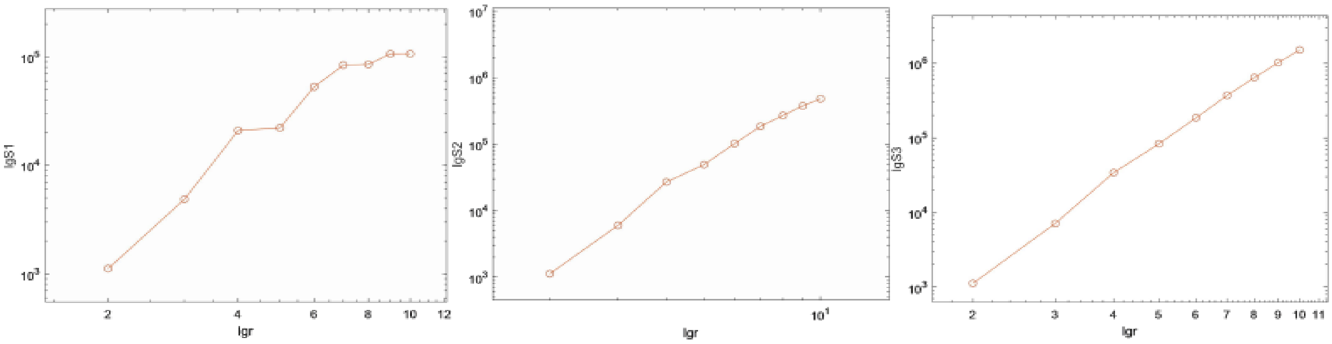

Figure 5: Multi-stage cumulative sum of landslide slope and volume

As shown in Figure 5, the S3-r double-logarithmic curve can be clearly fitted to a double-logarithmic form. Using MATLAB, the fractal dimension value D=-8.6268 for the third-order cumulative sum curve is obtained.

4.2 Fractal Characteristics of Volume and Elevation of Landslide

Elevation is a critical factor influencing landslide dynamics, as stability varies across different altitudes, which in turn affects the formation and distribution of landslides in various regions. Therefore, we will analyze the fractal characteristics of landslide volume versus elevation. For research convenience, this study divides elevation into equidistant intervals, starting from 1500m and proceeding in 50m increments until 1900m, with the final interval covering elevations above 1900m. In total, there are nine intervals.

Similarly, when r is defined as the elevation range, N(r) represents the landslide volume corresponding to that range, measured in 103m3. The collected data undergo statistical processing, including cumulative sum and variable dimension analysis formulas, followed by error correction to derive multi-order cumulative sums, as detailed in Tables 6, 7,8, and 9.

Similarly, the multi-stage cumulative sum is shown in Figure 6 after processing with MATLAB.

Table 6: Statistical table of landslide elevation interval

r	1	2	3	4	5	6	7	8	9
N(r) /103m3	7	276.15	11519	24934.2	15400	0	967	29000	23750

Table 7: First-order cumulative sum of landslide elevation interval and volumes

First-order cumulative sum	$S1_1$	$S1_2$	$S1_3$	$S1_4$	$S1_5$	$S1_6$	$S1_7$	$S1_8$	$S1_9$
accumulated value	7	283.15	11802.15	36736.35	52136.35	52136.35	53103.35	82103.35	105853.35

Table 8: Second-order cumulative sum of landslide elevation interval and volumes

Second-order cumulative sum	$S2_1$	$S2_2$	$S2_3$	$S2_4$	$S2_5$	$S2_6$	$S2_7$	$S2_8$	$S2_9$
accumulated value	7	290.15	12092.3	48828.65	100965	153101.35	206204.7	288308.05	394161.4

Table 9: Third-order cumulative sum of landslide elevation interval and volumes

Third-order cumulative sum	$S3_1$	$S3_2$	$S3_3$	$S3_4$	$S3_5$	$S3_6$	$S3_7$	$S3_8$	$S3_9$
accumulated value	7	297.15	12389.45	61218.1	162183.1	315284.45	521489.15	809797.22	1203958.6

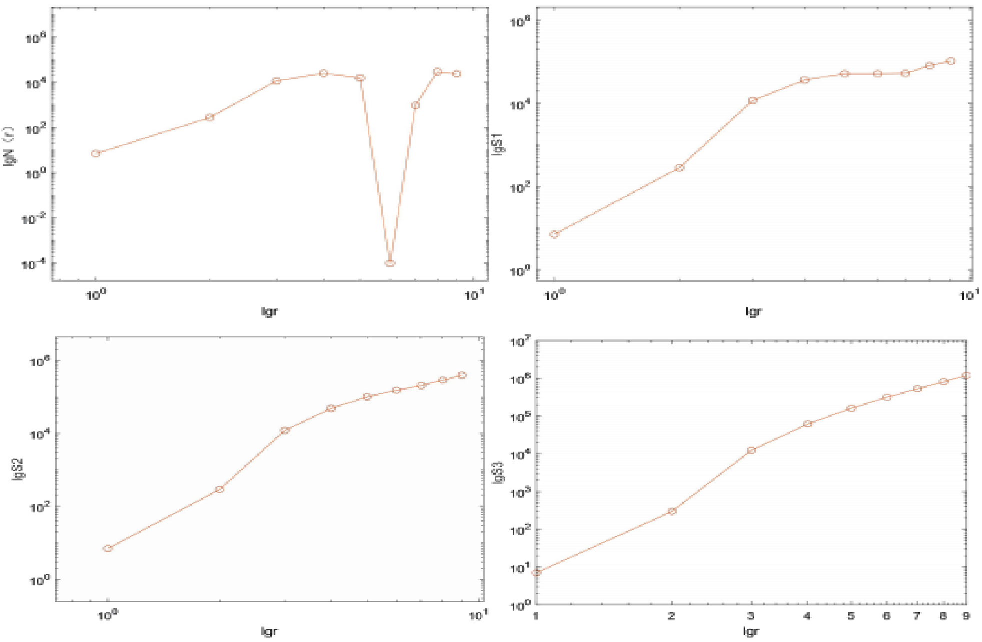

Figure 6: Multi-stage cumulative sum of landslide elevation and volume

Table 10: Fourth-order Cumulative Sum of Landslide Elevation Intervals and Volume

Fourth-order cumulant	S41	S42	S43	S44	S45	S46	S47	S48	S49
accumulated value	7	304.15	12693.6	73911.7	236094.8	551379.25	1072868.4	1882665.62	3086624.22

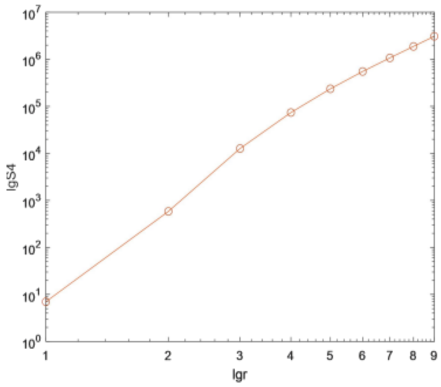

Figure 7: Fourth-order cumulative sum of landslide slope and volume

Through visual inspection, unlike the fractal characteristics of slope, the third-order cumulative sum curve still shows significant difficulty in fitting a straight line. At this stage, it is advisable to proceed with higher-order cumulative sum calculations (Table 10) and plot the cumulative sum graph (Figure 7).

As shown in Figure 7, the fourth-order cumulative sum of landslide slope and volume is more suitable for fitting the curve of volume and elevation, and the fractal dimension D =-4.3616.

4.3 Fractal Characteristics of Volume and Lithology of Landslide

The study of the fractal characteristics of rock types of landslide can better understand the formation mechanism of landslide, so the paper divides the characteristics of rock types of landslide according to the degree of hardness, r is the rock hardness ranking, and N(r) is the volume of landslide, unit is 103m3, finally get the multi-stage cumulative and Table 11, Table 12, Table 13 and Table 14.

Similarly, the multi-stage cumulative sum is shown in Figure 8 after processing with MATLAB.

Table 11: Statistical table of rock hardness interval of landslide

r	1	2	3	4	5	6	7	8	9
N(r) /103m3	1100	22470	2435	43043	20114.9	16920.2	7	23.25	400

Table 12: Rock hardness interval and first-order cumulative landslide volume of landslides

First-order cumulative sum	$S1_1$	$S1_2$	$S1_3$	$S1_4$	$S1_5$	$S1_6$	$S1_7$	$S1_8$	$S1_9$
accumulated value	1100	23570	26005	69048	89162.9	106083.1	106090.1	106113.35	106513.35

Table 13: Second-order cumulative sum of landslide rock hardness interval and volumes

Second-order cumulative sum	$S2_1$	$S2_2$	$S2_3$	$S2_4$	$S2_5$	$S2_6$	$S2_7$	$S2_8$	$S2_9$
accumulated value	1100	24670	50675	119723	208885.9	314969	421059.1	527172.45	633685.8

Table 14: Third-order cumulative sum of landslide rock hardness interval and volumes

Third-order cumulative sum	$S3_1$	$S3_2$	$S3_3$	$S3_4$	$S3_5$	$S3_6$	$S3_7$	$S3_8$	$S3_9$
accumulated value	1100	25770	76445	196168	405053.9	720022.9	1141082	1668254.45	2301940.25

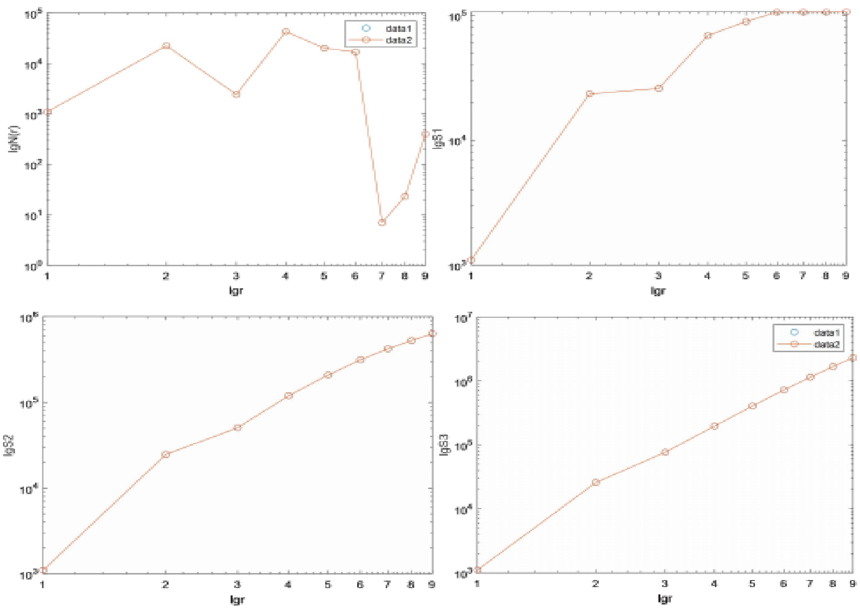

Figure 8: Multi-stage cumulative sum of landslide lithology and volume

The lithology of the landslide can be fitted to a straight line by the third-order cumulative sum curve, and the fractal parameter D=-3.3853.

4.4 Interpretation of Result

The spatial distribution of Lanzhou City in Gansu Province exhibits fractal characteristics of varying dimensions across different scales, influenced by factors such as slope, elevation, and lithology. Specifically, landslide slopes and lithology demonstrate third-order cumulative fractal behavior, while landslide elevations show fourth-order cumulative fractal equations. The fractal dimension values obtained in this study vary significantly, and statistical analysis yields fractal data tables for different factors (Table 15).

Table 15: Dimensional Fractal Data Table of Different Factors

Influencing factor, influence factor	Fractal dimension	Cumulative and Order
Slope,	D= -8.6268	III
Elevation	D= -4.3616	IV
Lithology	D= -3.3853	III

As fractal dimension serves as a statistical metric for measuring correlation between variables, it can be used to assess the relationship between landslides and other factors. The fractal dimension value reflects the degree of correlation between landslides and related factors. A higher fractal dimension indicates stronger correlation, while a lower value suggests weaker correlation and relatively minor impact. As shown in Table 15, comparing fractal dimension values reveals the following correlation order: slope> elevation> lithology.

5. Conclusions and Prospects

This study employs fractal theory and integrates software tools such as ArcGIS and Matlab to conduct an in-depth analysis of the spatial distribution patterns of landslides in Lanzhou City. Through a series of investigations, the following conclusions are drawn:

1) After the slope of the landslide in Lanzhou was analyzed by variable dimensional fractal analysis, it was found that the slope of the landslide showed three-order cumulative and variable dimensional fractal characteristics.

2) The fractal dimension analysis results show that the fractal dimension value of slope is large, which indicates that there are special geological conditions and complex terrain in some landslide areas of Lanzhou.

3) For the study area, the correlation ranking of landslide and its influencing factors is slope> elevation> lithology.

Through the experimental analysis of this paper, the distribution characteristics of landslides in Lanzhou can be further explored and the scientific basis for its prediction can be provided.

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