Front. Earth Sci. 2024, 18(1): 17−29
https://doi.org/10.1007/s11707-022-1033-y

RESEARCH ARTICLE

Morphological characteristics and evolution model of slope units along loess gully cross section

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Abstract Gully morphology is an important part of loess landform research. Along with gully development, the variation of its cross section is the most significant, and it can intuitively reflect the characteristics of the lateral widening of the gully slope. Therefore, in-depth research of the variation of the cross-sectional morphology of the gully is helpful to understanding the development process of the loess gully. Based on the DEMs (Digital Elevation Model) of nine periods of an indoor simulated loess small watershed, this paper studies the evolution model of a complete branch ditch in the watershed using the digital terrain analysis theory and method. Results show that with the development of the gully, the average gradient of the gully slope continuously decreases, and the slope morphology is mostly a concave slope along the slope direction. The degree of downward concave first increases and then gradually tends to be gentle. The gully erosion mode is gradually transformed from downward cutting erosion to lateral erosion. The more mature the gully development, the lower the depth of gully bottom cutting is compared with the width of gully widening. Furthermore, the surface cutting depth tends to be stable and the slope is stable. Then, the transformation law of the slope morphology of the gully cross section with the development of the gully is studied, and the prediction model of the transformation of the slope morphology of the gully cross section is established by using the Markov chain. The Markov model can better reflect the dynamic change of the slope morphology of the gully cross section, which is of great significance to revealing the external performance and internal mechanism of the gully morphology.

Keywords gully cross section, slope morphology, Markov chain, digital elevation model

Received January 18, 2022; accepted September 26, 2022

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1 Introduction

The Loess Plateau is the largest and most concentrated loess region in the world, with a unique formation reason and special geomorphic. It is one of the most important regions for geoscience research all over the world (Tang et al., 2015; Xiong et al., 2016). Thousands of loess gullies with different shapes and structures are formed on the surface of the Loess Plateau due to strong water erosion. A loess gully is the most dynamic, variable, and characteristic object unit in a loess landform, and it is also an important focus of loess landform research (Chen et al., 2021). Due to the special geographical conditions of the Loess Plateau, the morphology of loess gullies is significantly different from that of gullies in other regions. There are abrupt changes in the cross section of loess gullies, which are rarely seen in other gullies. With the evolution of gullies, the abrupt location of gully cross section also changes (Zhang et al., 2012). Loess gullies are one of the regions with the most frequent material transport in loess landforms, and the development process of gullies has a profound impact on the development and evolution of loess landforms (Li et al., 2022a). Research on the development and evolution of loess gully has important theoretical significance and broad applications for revealing the role of matter, energy, and time in shaping gully morphology, exploring the internal mechanism of loess gully formation and soil erosion, and guiding the ecological restoration and regional sustainable development of Loess Plateau (Chen et al., 2021).

The evolution of gullies in the Loess Plateau is not only closely related to the loess landform but to the movement and distribution of material and energy in the gully system (Zhu et al., 2014; Chen et al., 2021). According to the process of gully development (from low-level to high-level, from early to mature, and combined with morphological differences) loess gullies can be divided into six types: rill, shallow, dissected, wash, dry, and stream gully (Luo, 1956; Li et al., 2020a). Obvious differences occur in the morphological characteristics of various types of gullies, especially in their cross sections: the cross section of rill is a shallow 'V' shape, a shallow gully's is an inverted herringbone, a dissected and wash gullies' are "V" shaped, and the dry and stream gullies are "U" shaped (Zhou, 2006; Li et al., 2007; Na et al., 2016).

Gully morphology changes considerably with gully erosion, gravitational erosion, and other factors, with distinct regional differences and development stage differences. In turn, the gully morphology affects the process of gully erosion and gravitational erosion and then affects gully development (Frankl et al., 2013; Mukai, 2017). There are three different erosion modes of gully erosion in the Loess Plateau: headcut, lateral, and vertical undercutting. These three exist simultaneously in the process of gully development. Gully erosion is a four-dimensional spatial process that considers longitudinal, transverse, vertical, and time factors (Jing, 1986). Therefore, in gully development, the development is mainly manifested by the continuous advancement of the gully head; i.e., the vertical cutting and the horizontal expansion of a gully.

During gully development, with the deepening of the gully, the lateral erosion promotes the continuous evolution of the gully landform. The runoff continuously erodes and cuts the gully bank, causing gravitational collapse. The widening of a gully is the result of the joint action of lateral and gravitational erosion (Chen, 2010). However, existing studies mainly focus on the headcut at the gully head because studies on lateral erosion are faced with the difficulty of high data acquisition cost, limiting available quantitative research. Lateral erosion is one of the three methods of gully erosion. Through the comprehensive analysis of the morphological characteristics of the gully cross section, we can examine the development and evolution of the gully from a horizontal perspective, systematically and comprehensively study the morphological characteristics and regional differences of gullies and the degree of gully development, and further explore the internal mechanism and law of gully geomorphic evolution. Subsequent results provide important implications for the control of soil and water loss in the Loess Plateau (Lv et al., 2017; Xiong et al., 2021).

Scholars have used many indices to describe the morphological characteristics of the gully cross section. Gully morphology factors such as gully width, gully depth, and cross-sectional area can be accurately measured based on digital terrain analysis and remote sensing technology. Gully width measures the lateral erosion of a gully (Gabet and Bookter, 2008; Frankl et al., 2013), while gully depth measures the degree of downcutting erosion (Heede, 1970; Govers, 1987; Zucca et al., 2006). The gully cross-sectional area is also an important factor to measure the erosion area of the gully and a reflection of the comprehensive effect of the downcutting erosion and lateral erosion of the gully (Zhou et al., 2020). A positive correlation has been found between gully cross-sectional area and gully length (Nachtergaele and Poesen, 1999; Li et al., 2017). Factors such as the width-depth ratio and shape index have been proposed to describe the development stage of a gully (Cao et al., 2021).

The width-depth ratio is used to describe the relationship between lateral erosion and downcutting erosion (Zucca et al., 2006; Gabet and Bookter, 2008). Controlled by both bedrock and datum, the width-depth ratio of a single gully usually increases when going downhill (Gabet and Bookter, 2008). The shape index is used to distinguish between U- and V-shaped cross sections (Wu et al., 2018) where the low value is related to the V-shaped cross section and the high value is related to the U-shaped cross section (Gabet and Bookter, 2008; Wu et al., 2018). The shape index does not show the variation trend of distance along the gully but expresses the evolution stage of the gully (Heede, 1970).

The process of gully evolution is the process of a gully continuously eroding and cutting the surface (Jing, 1986). To quantitatively study the process of gully evolution, scholars have established several models to reflect gully erosion according to influencing factors (Douglas-Mankin et al., 2020). Gully erosion model is a mathematical expression to express the quantitative relationship between gully generation, development, evolution process, erosion amount, and the main influencing factors of gully erosion. The existing research on gully erosion model mainly focuses on the prediction model of erosion amount and the evolution model of gully erosion process. The EUROSEM model divides erosion into inter-rill and rill erosion and builds a distributed erosion model considering the influence of vegetation and rainfall kinetic energy (Morgan et al., 1998).

Some scholars also believe that the gully erosion process is similar to the development process of river knickpoint, and the knickpoint erosion model has also been used in the simulation of gully erosion (Montgomery and Foufoula-Georgiou, 1993; Berlin and Anderson, 2007; Royden and Taylor Perron, 2013; Martins et al., 2017). There are also many other models proposed by scholars, such as the EGEM and WEPP models (Woodward, 1999; Nachtergaele et al., 2001; Flanagan et al., 2012; Hancock and Willgoose, 2021; Tekwa et al., 2021). These studies have deepened the understanding of the gully development mechanism. However, most of them focused on the overall situation but have not paid enough attention to the gully cross section.

Lateral erosion is one of the three important ways a gully erodes. Extracting and analyzing the cross sections of different gullies and different spatial positions of gullies in the basin has important implications for research on the morphological characteristics, development and evolution, and soil erosion of gully landforms. However, the information on the morphological characteristics contained in the gully cross section have not been effectively explored. The current research on the loess gully cross sections remains in the qualitative discussion of its “U” to “V” shape, lacking the quantitative expression and the analysis of differences of the cross-section morphology based on a time scale. Based on the artificial simulated DEM (Digital Elevation Model) data of multi-stage erosion development of small loess watershed, the slope surface of the small watershed is segmented and extracted and a series of topographic factors of the small watershed are calculated in the unit of slope unit to quantitatively describe the morphological characteristics of the loess gully cross section. The transformation law of slope morphology of gully cross section with the gully development is studied. Hence, the morphological evolution process of the loess gully slope is simulated and predicted based on the Markov chain.

2 Study area

Owing to the extremely slow development process of a gully, obtaining multi-period data on a long time scale is difficult. In this study, relevant experiments were carried out based on a loess simulated small watershed under the condition of artificial rainfall. The test data was extracted from the soil erosion and rainfall erosion simulation test of the State Key Laboratory of Dryland Agriculture on the Loess Plateau (Cui, 2002). Test soil was taken from Yangling loess in Shaanxi Province, with an average density of 1.39 g/cm^3. The maximum length of the test chamber is 9.1 m, the maximum width is 5.8 m, the total perimeter is 23.3 m, the maximum height difference is 2.57 m, and the average slope is 15 degrees. In the simulation test, the horizontal filling was carried out in units of 5 cm and each layer was filled and compacted to ensure that the two adjacent layers of fillers are closely connected and that the filler met the design requirements.

In the simulated rainfall hall of the State Key Laboratory of Soil Erosion and Dry Farming on the Loess Plateau, the simulated rainfall experiment was carried out using a sprinkler rainfall system. The nozzle height was at 16 m, the rainfall intensity varied in the range of 30–120 mm/h, and the rainfall uniformity was more than 80%. The rainfall area consisted of two independent rainfall test areas, which can be combined with rainfall. The effective rainfall area of a single test area was 27 m × 18 m, and the total area was 2 × 27 m × 18 m. The rainfall process can be completely controlled by computer according to the test requirements.

High-precision close-range photogrammetry technology was used during the experiment to dynamically monitor the topographic changes of the watershed model and the topographic measurements were carried out after each rainfall. The DEM production process of the ninth-period loess simulated small watershed is as follows. First, the simulated small watershed was photographed nine times through close-range photogrammetry, the stereo pairs were obtained at different development stages, and the interval between two periods was about one week or two. Second, the data was processed, generating high-resolution DEM through model making. The main parameters of DEM data were as follows: DEM horizontal resolution is 10 mm and elevation mean square error is less than or equal to 2 mm. The basic morphological characteristic indexes of the simulated small watershed are shown in Table 1.

The sample area of the loess simulation small watershed is shown in Fig. 1 below. Given that no gullies were present in the small watershed in the first stage, this paper mainly uses the second to the ninth stages as the study plots for the study of the morphological characteristics of the gully cross section on a time scale.

3 Research methods

3.1 Segmentation and extraction of slope units based on the information of terrain skeleton

3.1.1 Segmentation and classification of slope units

This study extracts slope, plan curvature and profile curvature from slope morphology following DEM data. Based on the location information of loess gullies, ridges and gullies are extracted as the topographic skeleton of the slope (Lv et al., 2017; Xiong et al., 2021). To avoid the influence of different dimensions, all the terrain factors were normalized and matched with the gray value of the image. Then multi-band image was synthesized by normalized DEM and five derived layers. The multi-scale segmentation method was used to segment the image by selecting appropriate band weight, scale parameters, shape index, and compactness index (Drăguţ and Blaschke, 2006; Wang et al., 2014; Li et al., 2020b; Li et al., 2022b). As a new remote sensing image processing method, multi-scale segmentation technology has been paid close attention by researchers. Traditional feature information extraction technology defines the minimum

Table 1 Basic morphological characteristics index of simulated small watershed (according to Cui (2002))

Projected area/m^2	Length of watershed/m	Maximum width/m	Perimeter/m	Elevation difference/m	Longitudinal gradient of watershed/%	Average slope/(°)	Channel level
31.49	9.1	5.8	23.3	2.57	28.24	15	2

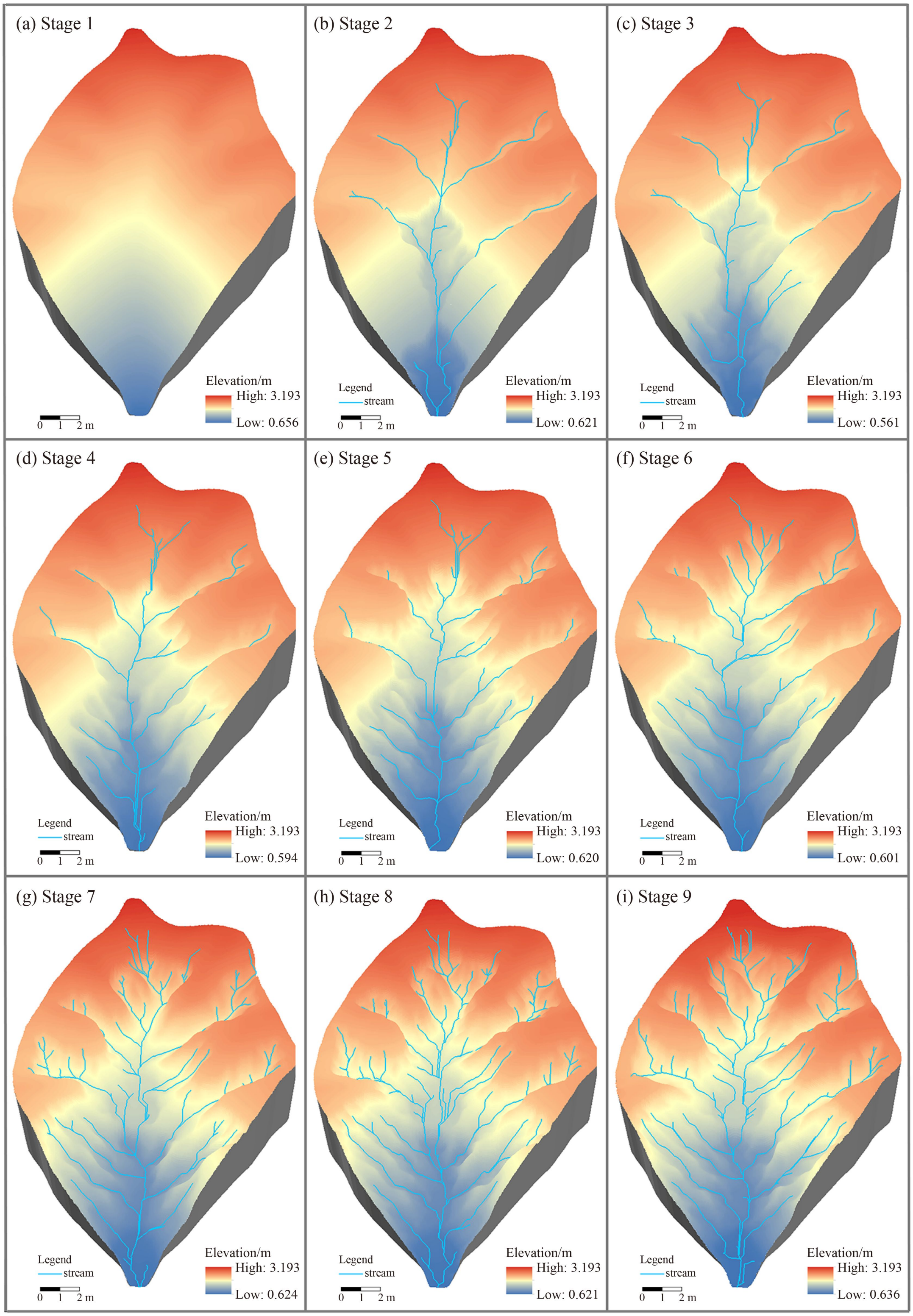


Fig. 1 Sample area map of loess simulation small watershed.

unit of feature information as a single pixel, while multi-scale segmentation technology focuses on the image object itself, effectively avoiding the classification noise in pixel analysis, reduce the homogeneity of different features and the heterogeneity of similar features, and then improve the classification separability (Eisank et al., 2014).

The algorithm sets specific thresholds for image segmentation according to the shape, color, and relationship between different features and surrounding features.

It extracts different levels of image objects according to different scales in the same resolution image and optimizes the segmentation results to a great extent (Wang et al., 2016). The image to be segmented contained six bands, which had the same contribution value in the process of terrain segmentation. We assigned the weights of the six bands to 1. Segmentation scale is the threshold where the polygon image objects stop merging in the multi-scale segmentation algorithm and is the most important parameter in multi-scale segmentation (Karami et al., 2015). While segmenting, large segmentation scale will segment larger image objects and smaller number of objects, and a small segmentation scale will get more target image objects, and the area of image objects is also small. This paper uses the eCognition plug-in ESP2 developed by Drăgut to calculate the ROC-LV diagram and determine the optimal scale parameters of sample areas (Drăguţ et al., 2010, 2014). The shape index and compactness index also affect the final result of segmentation, and the segmentation results obtained by different parameter combinations are also different. Generally, the smaller the shape index is, the more the number of segmented objects and the finer the segmentation result. And the smaller the compactness is the rougher the boundary of the segmentation result. Usually, the combination of control variables and visual discrimination is used to select the appropriate parameters.

Aiming at the morphological feature analysis of image objects and considering the characteristic terrain elements combined with slope morphology and slope position, the slope unit is divided into five categories (Drăguţ and Blaschke, 2006; Wang et al., 2014; Li et al., 2020b; Li et al., 2022b), as shown in Table 2, where the segmented image objects are divided according to the following rules.

a) Image objects with ridge values greater than 0.5 are classified as ridges.

b) Image objects with valley values greater than 0.5 are classified as valleys.

c) Using profile curvature as a measure, the remaining unclassified image objects are classified into convex, straight, and concave slopes using the membership function (Qin et al., 2009; Zhu et al., 2018).

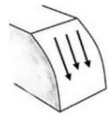
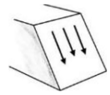
Finally, the classification results of slope units in the indoor simulated small watershed of loess are obtained, as shown in Fig. 2.

3.1.2 Extraction of slope unit in gully cross section

Section lines are manually arranged along the loess gully at intervals of the width of slope units, and the slope units intersecting with the section lines are also extracted. The same slope unit has only a single gully cross section line intersecting it. This cross section line is perpendicular to the direction of the gully as far as possible, spans both sides of the main gully, extends to the watershed boundary line, and avoids the tributaries of the main gully as far as possible. Figure 3 is a schematic diagram of extracting slope units along the cross section line of the gully.

With continuous gully erosion, various branch gullies are developed in the main gully of the simulated small watershed and some branch gullies with the main gully. Avoiding the branch gullies and laying cross section lines on the main gully is difficult. Therefore, this paper selects four primary branch gullies with clear, well-developed main gullies coinciding with the layout principle to lay section lines, which are L1, L2, R1, and R2 from left to right and from bottom to top, as shown in Fig. 4 below.

Table 2 Category description of slope units

Name	Slope morphology	Profile curvature	Terrain control information
Convex slope		Profile < 0	—
Straight slope		Profile = 0	—
Concave slope		Profile > 0	—
Ridge	—	—	Ridge > 0
Valley	—	—	Valley > 0

3.2 Quantitative index of morphological characteristics of loess gully slope

Here, the quantitative indicators of characteristics of loess gully slope units were designed and selected from three aspects: gradient of the slope unit, the horizontal and vertical concave-convex degree of the surface, and the degree of erosion and cutting of the surface as shown in Table 3.

4 Results

4.1 Analysis on slope morphological characteristics of gully cross section

4.1.1 Average slope

During gully development, the bottom and slope of the gully are slowly decreasing, and the average slope is gradually decreasing. Following Fig. 5, the variation diagram of the average slope of gullies in the simulated small watershed in all nine stages is shown. The slope of each gully is the average value of all sampling cross-sectional slope units of the gully in this stage. The average slope of the four branch ditches decreases with gully development. The average slope of gully L2 and R1

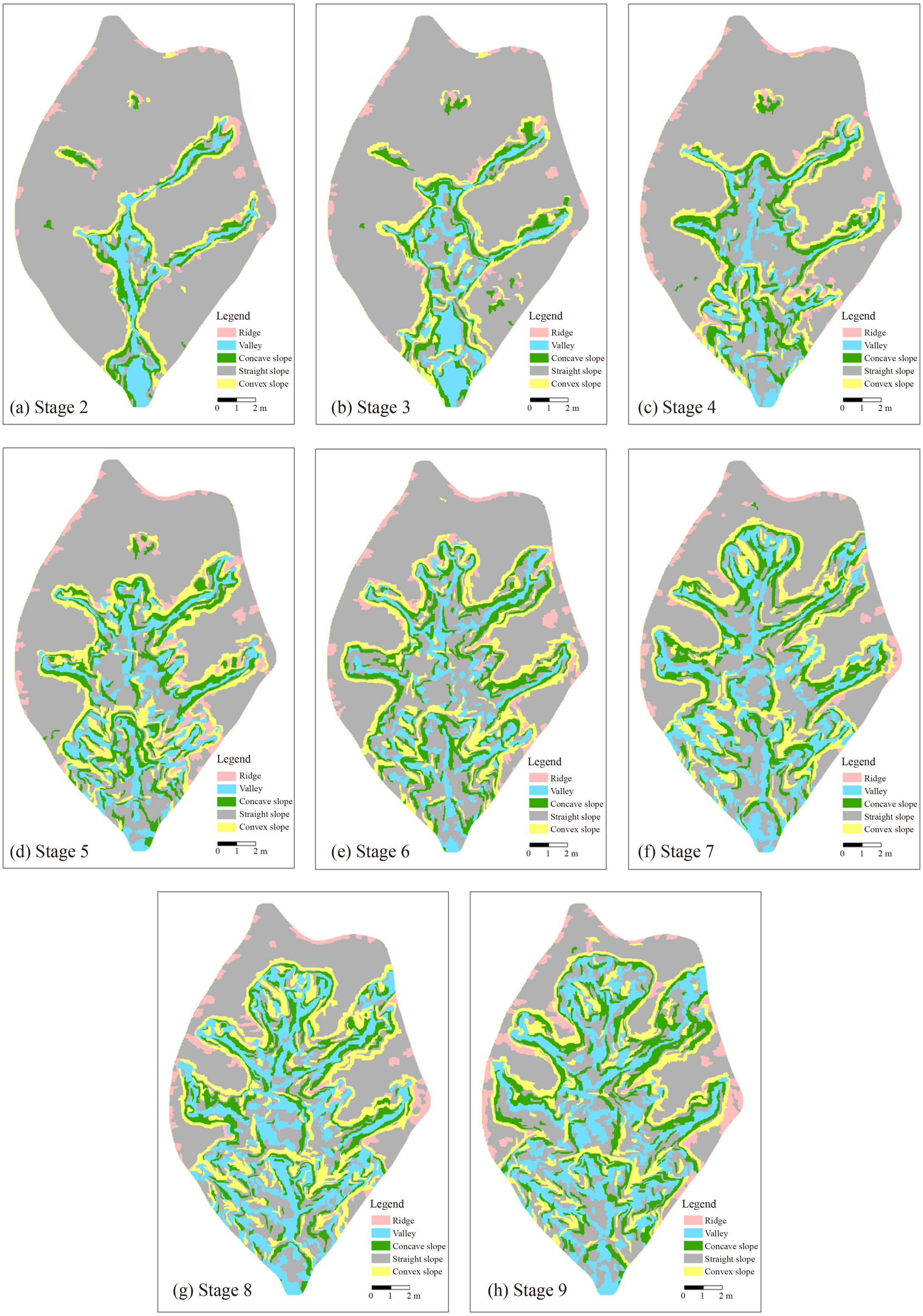


Fig. 2 Slope classification results of simulated small watershed.

decreases slowly from stage 2 to stage 9. Then, average slope of gully L1 decreases rapidly from stage 2 to stage 3 and then decreases slowly. Last, the average slope of gully R2 from stage 8 to stage 9 decreases faster than that of the previous seven stages.

4.1.2 Curvature

As shown in Fig. 6, the variation diagram of slope curvature in nine stages of the simulated small watershed is shown. The curvature of each gully is the average

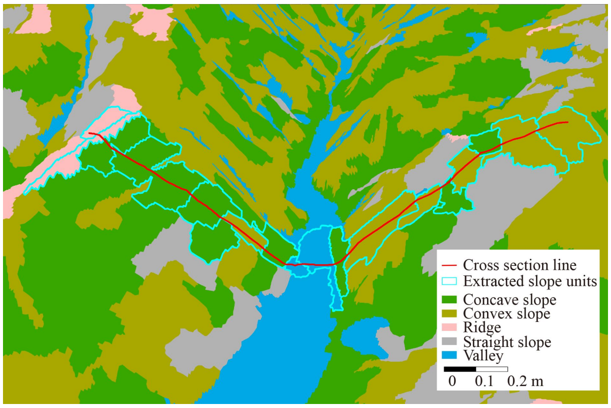


Fig. 3 Schematic diagram of extracting slope units along a cross section line.

curvature of all sampled cross-sectional slope units of the gully in this stage. The plan curvature of the four branch ditches increased continuously from stage 2 to stage 9. Before stage 4, gullies L1 and R2 were negative and the slope morphology was mainly concave along the contour line. From stage 4, the plan curvature of the slope was greater than 0, and the slope morphology changed to mainly protruding outward along the contour line, and the degree of average protruding continued to strengthen. The concave-convex boundary period of gully R1 is stage 5 and L2 is stage 6. The slope morphology along the contour line changes from inward concave to outward convex, and the degree of convexity increases continuously. The runoff changes slowly from confluence to dispersion on the slope and the intensity of gully erosion decreases gradually. The profile curvature of the

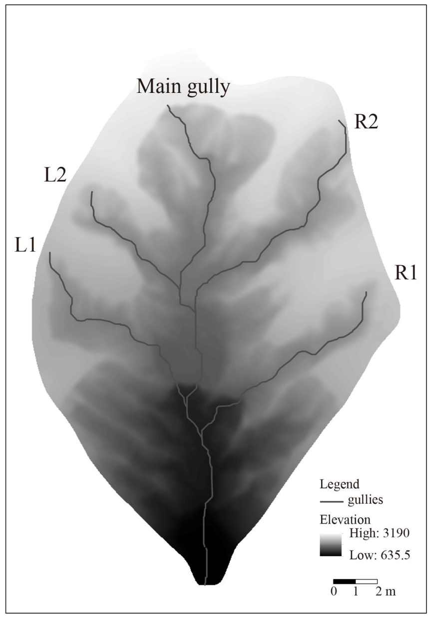


Fig. 4 Spatial distribution map of gullies in loess simulated small watershed.

Table 3 Quantitative index of morphological characteristics of loess gully slope units

Average slope	Index definition	Average value of the slope of the trench slope unit
	Description and expression	$\text{Slope} = \arctan\sqrt{f_x^2 + f_y^2}$ where f_x is the rate of elevation change in the north–south direction, f_y is the rate of elevation change in the east–west direction
	Significance	It reflects the morphological characteristics of the slope
Plan curvature	Index definition	Curvature of the ground contour at each point
	Description and expression	$K_h = -\dfrac{f_{xx}f_y^2 - 2f_{xy}f_xf_y + f_{yy}f_x^2}{(f_x^2+f_y^2)\sqrt{\sqrt{1+f_x^2+f_y^2}}}$ where f_{xx}, f_{xy} and f_{yy} are the rate of second-order elevation change of the x and y directions
	Significance	Reflects the degree of curvature and changes of the surface along the horizontal direction. The positive slope surface is convex outward, and the negative slope surface is concave inward.
Profile curvature	Index definition	Rate of change of ground slope along the direction of maximum gradient
	Description and expression	$K_v = -\dfrac{f_{xx}f_x^2 + 2f_{xy}f_xf_y + f_{yy}f_y^2}{(f_x^2+f_y^2)\sqrt{\sqrt{1+f_x^2+f_y^2}}}$ where f_{xx}, f_{xy} and f_{yy} are the rate of second-order elevation change of the x and y directions
	Significance	Reflects the degree of curvature and change of surface along the slope direction. The positive slope surface is concave inward, and the negative slope surface is convex outward
Surface cutting depth	Index definition	Difference between the average elevation and the minimum elevation within a certain neighborhood of a point on the ground
	Description and expression	$G_i = H_{\text{mean}} - H_{\text{min}}$ where H_{mean} is the average elevation of a certain point on the ground within a certain neighborhood, H_{min} is the lowest elevation of the point within the same neighborhood
	Significance	Directly reflects the degree of surface erosion and cutting of the gully slope unit. The larger the index value, the more intense the surface erosion cutting, and the higher the development degree of gully undercutting

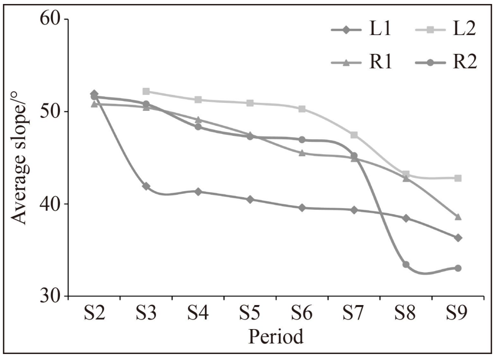


Fig. 5 Variation diagram of average slope of gully slope in simulated small watershed.

four gullies is positive from stage 2 to stage 9 and continues to rise. The slope morphology is mostly concave along the slope direction, and the runoff velocity on the upper slope is greater than that on the lower slope. The runoff is a rapid flow, but the lower slope can intercept the erosion sediment from the upper slope so the entire slope tends to be stable.

4.1.3 Surface cutting depth

Following Fig. 7, the surface cutting depth of the slope in the simulated small watershed is calculated by averaging the surface cutting depth of all slope units intersecting with the cross section in the negative terrain. In this stage, the surface cutting depth of each gully is the average value of all sampled cross-sectional slope units of the gully. Taking the slope unit as another unit, the average surface cutting depth continuously decreases from stages 2 to 9. From stages 2 to 4, the surface cutting depth decreases faster. From stages 5 to 7, the surface cutting depth decreases more slowly. After stage 7, the surface cutting depth reaches a stable level. From stages 2 to 4, the overall downcutting erosion of the gully bottom is strong. Overall, the gully bottom and gully slope are decreasing, and the surface cutting depth is decreasing. From stages 5 to 7, the gully gradually changed from undercutting to lateral erosion, the overall trend of gully slope continued to slow down, and the rate of surface cutting depth slowed down. After stage 7, the gully is dominated by lateral erosion, the height of the gully bottom changes only slightly, the gully slope decreases slowly, and the surface cutting depth tends to be stable.

4.2 Analysis of slope morphological evolution of gully cross section

The morphology of the gully cross section and the slope morphology intersected by the cross section affect and interact with the evolution process of the surface morphology. The cross section reflects the stage of the development and evolution of the gully and the intensity of gully erosion. The slope morphology is the micro-unit of the surface and an important decisive factor in the collection process of runoff, and the process and degree of soil erosion also changes. Therefore, the evolution process of the gully can also be regarded as the process of morphological change of the gully cross section, mutual transformation of slope morphological types and mutual substitution in spatial position. Research on gully cross section and its slope morphology has become particularly important. Here, gully R2 of the simulated small watershed is selected to track and study the transformation law of the slope morphology of the cross section.

With gully development, the slope morphology of the gully is constantly developing and changing. To explore the evolution law of slope morphology on the gully cross

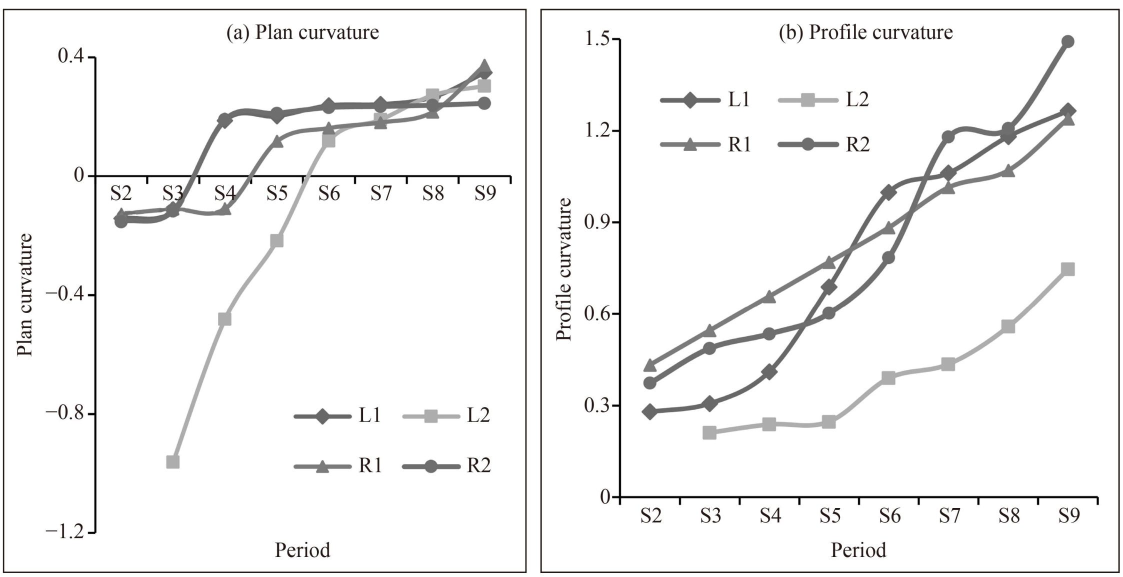


Fig. 6 Variation diagram of slope curvature in simulated small watershed.

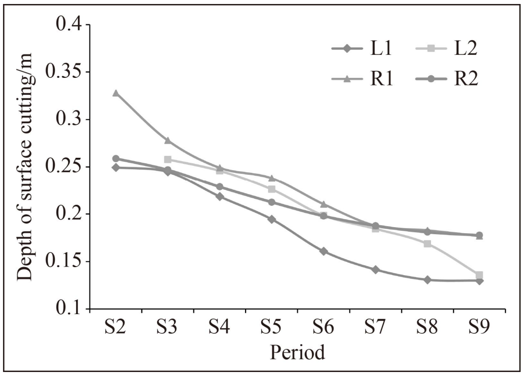


Fig. 7 Variation diagram of surface cutting depth in simulated small watershed.

section, this section takes the slope morphology at the initial stage as the original slope morphology, counts the transformation of slope unit to other slope morphology at the end of the time, and obtains the transformation map of seven stages of four slope shapes, as shown in Fig. 8. Since the research object is slope units of gully cross section located in the negative terrain, and the ridge does not belong to the negative terrain, the transformation of ridge is temporarily overlooked.

During the seven stages, the transformation laws of the four slope shapes to other slope shapes are basically the same. The concave slope was mainly transformed into a straight slope and valley. The concave slope was eroded by water and gradually evolved into a straight slope. With the gully development, the gully bottom continues to widen and the concave slope at the foot of the slope continues to evolve into a valley. For convex slope, the area converted to a concave slope is the largest, followed by a straight slope. Moreover, Fig. 8(b) shows that the closer to stage 9, the more the area transformed from a

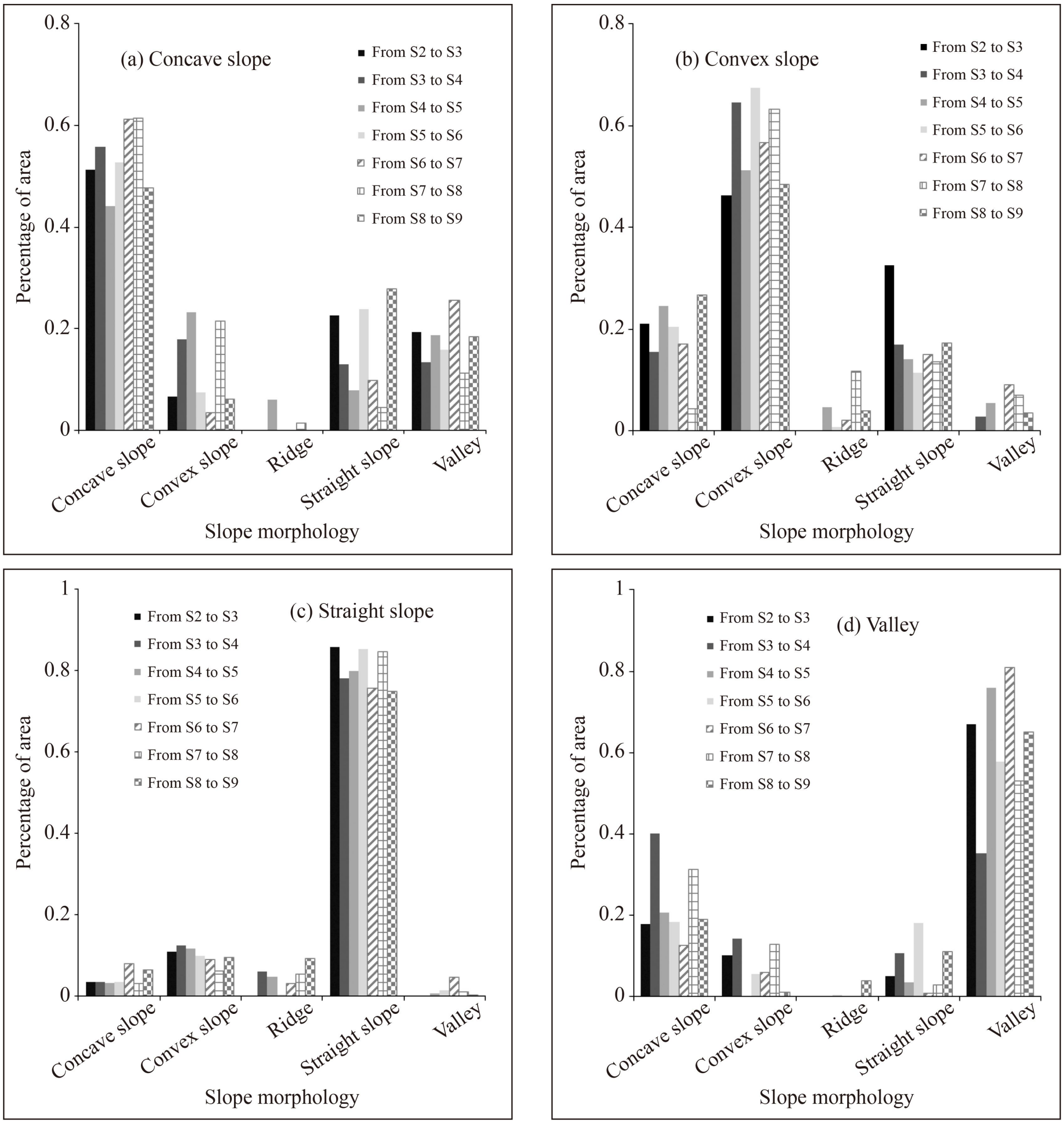


Fig. 8 Percentage of slope shape transformation area of cross section in loess small watershed.

convex slope to a concave slope and the less the area transformed to a straight slope. As the gully develops, the convex slope evolves to a straight slope first and then to a stable concave slope slowly after erosion. During evolution, most of the straight slope remains as is and a small part transforms into convex and concave slopes. The water and soil loss of straight slope is the largest, followed by convex slope, and the longitudinal concave slope is the smallest. The longitudinal concave slope is not easily eroded. Therefore, the straight slope is transformed into a convex slope and a concave slope. For the valley, most of the area is still a valley during seven stages. With the undercutting of the gully bottom, part of the area is transformed into a concave slope. The weaker the undercutting erosion in the later stage, the less the transformed area.

4.3 Simulation and prediction of slope morphological evolution of gully cross section

The slope morphology of a gully is the result of many factors, including topography, rainfall, and human activities (Berger et al., 2010; Ran et al., 2018; Guo et al., 2019). Gradient and slope length are the external manifestations of slope morphology, affecting the erosion process that occurs on the slope. Simultaneously, the erosion of flowing water constantly shapes the slope, and gravitational erosion leads to slope collapse and landslide, forming a completely different slope morphology (Fox and Bryan, 2000; Rieke-Zapp and Nearing, 2005; Sun et al., 2013; Zhang et al., 2019; Sun et al., 2021). Human beings building terraces and planting trees cannot only affect the shaping process of slope but also directly change the slope morphology. Therefore, similar to the uncertainty of the transformation between various land use types in the evolution of land use, the transformation of slope types from one type to another has a certain randomness (Guan et al., 2008).

The Markov chain is a stochastic process proposed by Russian mathematician Andrey Markov from 1906 to 1907. Here, under the condition of given information, the future state is only related to the current state but independent of the previous historical state. The system transfers from one state to another with the characteristics of no aftereffect and stability (Iacono et al., 2015; Ghosh et al., 2017; Paul et al., 2018). The slope morphology of a gully is the result of the joint action of many factors. In a certain area, different slope types may transform each other, and the mutual transformation process between different slope types includes many events that are difficult to be accurately described by special functions. The dynamic transformation between slope types is the nature of the Markov process. Therefore, in this section, the Markov chain is used to establish a prediction model for the transformation of the cross-sectional slope morphology of the indoor simulated small watershed. The key to using the Markov model for prediction is to determine its transition probability at m time, and the expression of its transition matrix is

$$P = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ P_{n1} & P_{n2} & \cdots & P_{nn} \end{bmatrix}. \tag{1}$$

The Markov prediction model based on the above transition matrix is

$$S^{(k+1)} = S^{(k)} \cdot P = S^{(0)} \cdot P^{(k+1)}, \tag{2}$$

where $S^{(k+1)}$ represents the state vector of the system at $t = k+1$, which is the prediction result. $P^{(k+1)}$ represents the transition matrix at $t = k+1$. $S^{(0)}$ is the initial state vector of the system. $S^{(k)}$ is the state vector of $t = k$. P_{ij} is the conversion probability of type i to type j in the study period. The prediction result of the Markov chain is determined by the initial state vector and transition matrix (Balzter, 2000; Sang et al., 2011).

In this section, the slope shapes of the cross section from stages 2 to 8 are used as training data to establish a Markov chain for cross-sectional slope prediction, and the model is verified by using the slope shape of the gully cross section in stage 9. First, calculate the transfer matrix of every two stages from stages 2 to 8, and then calculate the average value of the seven transfer matrices to construct the average transfer matrix from stages 2 to 8, as shown in Table 4.

The initial state matrix is composed of the percentage of slope area of each category in the cross section of stage 8 indoor simulated small watershed, as shown in Table 5. By introducing the initial state matrix and transition probability matrix into Eq. (2), the percentage of each slope type area of the cross section of the simulated small watershed at a certain time in the future can be obtained to simulate the evolution of the slope morphology of the gully cross section.

Table 6 shows the prediction results from stages 8 to 9 and the actual value of the slope area percentage of the gully cross section in stage 9, as well as the prediction error of the model. Here, the calculation formula of the prediction error of the model is

Table 4 Average transition matrix from stage 2 to stage 8 (one step is one period)

Item	Concave slope	Convex slope	Ridge	Straight slope	Valley
Concave slope	0.54	0.13	0.01	0.14	0.17
Convex slope	0.17	0.58	0.03	0.17	0.04
Ridge	0.19	0.24	0.25	0.32	0.00
Straight slope	0.10	0.10	0.02	0.70	0.07
Valley	0.19	0.09	0.01	0.14	0.56

Table 5 Area proportion of slope type in cross section of simulated small watershed in stage 8

Type	Concave slope	Convex slope	Ridge	Straight slope	Valley
Proportion	0.18	0.21	0.10	0.41	0.11

Table 6 Accuracy verification of Markov chain prediction model

Type	Concave slope	Convex slope	Ridge	Straight slope	Valley
Prediction	0.21	0.22	0.04	0.39	0.13
Actual	0.20	0.20	0.06	0.42	0.12
Error	5.95%	6.63%	53.54%	6.15%	8.41%

$$\text{Error} = \frac{|\text{Actual} - \text{Prediction}|}{\text{Prediction}} \times 100\%. \quad (3)$$

Except for the large error between the predicted value of ridge and the actual value, among the other slope types, the accuracy of concave slope type is the highest, followed by that of straight slope and convex slope, and the error of valley is the largest among the four types. The area of the ridge is small as well. In the early stage and active stage of gully development, the gully is continuously widened, eroding the ridge between branches. The ridge is transformed into other types. Because gully development tends to be stable, the change of positive terrain gradually decreases and the transformation of ridge tends to be stable, which is greatly affected by the lack of aftereffect. Thus, the simulation accuracy is low.

5 Discussion and conclusions

Taking the indoor simulated small watershed as the research object, combined with the theory and method of digital terrain analysis, this paper makes a comprehensive analysis of the gully cross section and its slope morphology, systematically and comprehensively studies the morphological characteristics of the gully, and further explores the internal mechanism and law of the evolution of the gully landform. Experiments show that with gully development, water erosion continuously acts on the slope, the gully bottom continues to widen, the gully slope continues to retreat and gradually slows down, and the average slope continues to decrease. The slope is mostly concave along the slope direction, and the degree of downward concave first increases and then gradually becomes gentle. The gully erosion mode gradually changes from downward cutting erosion to lateral erosion, and the more mature the gully development, compared with the width of gully widening, the depth of gully bottom cutting is even smaller, the surface cutting depth tends to be stable, and the slope tends to be stable.

We then studied the transformation law of slope morphology of cross section with the development of gullies. During the seven stages, the transformation laws of the four slope shapes to other slope shapes are basically the same. The concave slope was mainly transformed into a straight slope and valley. For convex slope, the area converted to a concave slope is the largest, followed by a straight slope. During evolution, most of the straight slope and valley remain so. On this foundation, a prediction model for the transformation of slope morphology of gully cross section is established using the Markov chain. Other than a large error between the predicted value and the actual value of the ridge, the prediction results of other slope types are good, proving that the model better reflects the dynamic changes of slope morphology of gully cross section.

In this study, the gully cross section is analyzed from different development stages and the geomorphic characteristics and transformation laws of the loess gully are deeply studied from the horizontal perspective. This provides new insights for understanding the formation and evolution of gully landforms and has significant implications for soil erosion management on the Loess Plateau.

However, the mechanism and process of the joint action of various factors of slope morphology are very complex. This paper only makes a preliminary exploration of the transformation and prediction of slope morphology by using the Markov chain. The Markov chain is a stochastic model, and the state and time of the system have no aftereffect. However, because the transformation of the slope morphology does not fully meet the requirements of no aftereffect, the valley is greatly affected by the lack of an aftereffect and the accuracy is low. The indoor small watershed data of loess is ideal, so the Markov chain model established in this paper is only an approximate model. If we want to predict the slope morphology in the medium and long-term, we need to further select a better model for simulation. Moreover, the indoor simulated small watershed is greatly affected by its engineered nature, which is different from the loess small watershed in the field. For future studies, we hope that research can be carried out based on multi-stage field gully data and gully cross-sectional morphology, and that the evolution law of slope morphology can be further explored so that the results obtained have more practical value.

Acknowledgment We are grateful for the financial support from the National Natural Science Foundation of China (Grant Nos. 41930102 and 41571383). We sincerely appreciate the Editor's encouragement. The constructive criticisms and suggestions from anonymous reviewers are also gratefully acknowledged.

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