Postprint: Variability Characteristics of Loess Erosion Slopes Under Simulated Rainfall Conditions

Authors: Zhao Weidong, Zhang Haonan, Jiang Qiong, Wei Jiajia, Zheng Yong, Zhao Weidong

Date: 2019-08-02T00:00:00+00:00

Abstract

Based on nine-phase DEM data of loess slope erosion obtained from indoor artificial rainfall experiments, the slope gradient, aspect, and gully network of the loess slope at different evolutionary stages were calculated. The variation characteristics of slope erosion were investigated using equal-interval slope histograms, equal-interval aspect rose diagrams, and hierarchical gully networks, and a preliminary analysis was conducted on the relationship between these variation characteristics and the erosion and evolution processes of the loess slope. The results indicate that: during the loess slope erosion process, the degree of slope gradient dispersion of the slope gradually increased and then remained essentially stable; its dominant slope aspect exhibited a progressively ordered variation characteristic overall, evolving from multiple dominant aspects to a single dominant aspect that was essentially consistent with the overall orientation of the main gully on the slope; and its gully network gradually developed into a typical dendritic network and remained essentially stable, forming a complete and rigorous hierarchical gully structure. These variation characteristics of the eroded slope reflect to some extent that erosion was relatively intense during the initial development stage of the slope but weakened in intensity during the later stage. This study represents a preliminary exploration of the variation characteristics of eroded loess slopes and holds important theoretical significance for further revealing the erosion mechanisms and evolution patterns of loess slopes in the future.

Full Text

Preamble

DOI: 10.12118/j.issn.1000-6060.2019.04.18
Journal: Arid Land Geography (ChinaXiv Cooperative Journal)

Authors: ZHAO Wei-dong[1,2,3], ZHANG Hao-nan[1,2], JIANG Qiong[3], WEI Jia-jia[1,2], ZHENG Yong[1]

Affiliations: 1. School of Resource & Environmental Engineering, Hefei University of Technology, Hefei 230009, Anhui, China 2. Intelligent Manufacturing Technology Institute, Hefei University of Technology, Hefei 230088, Anhui, China 3. School of Civil and Hydraulic Engineering, Hefei University of Technology, Hefei 230009, Anhui, China

Abstract: The erosion mechanism of loess hillsides and their landform variation characteristics during erosion require further research. Therefore, based on nine-phase DEM data of erosion and evolution of a loess hillside obtained from indoor artificial rainfall experiments at Yangling District, Shaanxi Province, China, the slope, aspect, and channel networks of the loess hillside in different evolution periods have been calculated. We used the slope histogram, the rose diagram of aspect, and the channel network to study the variation characteristics of the erosion process of the loess hillside, and preliminarily analyzed the relationship between the variation characteristics and the erosion and evolution process of the loess hillside. The results show that the slope dispersion degree of the loess hillside is basically stable after gradually increasing during the erosion process. The dominant aspects of the loess hillside show a gradual, orderly change and gradually evolve from a plurality of dominant aspects to a dominant aspect that is basically consistent with the overall orientation of the main channel of the loess hillside. The channel network gradually develops into a typical tree network, and remains basically stable, forming a complete and strict channel hierarchy. The above-mentioned variation characteristics of the loess hillside reflect that the hillside is eroded strongly during its prophase but weakened during its activity stage. This study is a preliminary exploration of the variation characteristics of loess erosion hillside, and it has important theoretical significance for further revealing the erosion mechanism and evolution law of loess hillside.

Keywords: loess erosion; geomorphological evolution; digital elevation model; artificial rainfall; slope erosion

Funding: National Natural Science Foundation of China (41272251); National Natural Science Foundation of China (1508085MD62); Anhui Provincial Natural Science Foundation (2012VGE04); Anhui Provincial University Excellent Young Talent Support Program (2012AHST0802)

Corresponding Author: ZHAO Wei-dong (1969-), male, native of Shandong, professor, research interests include DEM analysis and erosion processes. E-mail: zhaowd@hfut.edu.cn

1. Introduction

The erosion process and landform evolution of loess hillsides represent a critical area of research in geomorphology. Based on digital elevation model (DEM) data derived from artificial rainfall experiments, this study investigates the dynamic changes in slope, aspect, and channel network characteristics during the erosion evolution of loess hillsides. The research aims to establish quantitative relationships between geomorphometric parameters and erosion stages, providing theoretical insights into the mechanisms controlling loess landform development.

2.2 Slope Analysis and Channel Network Density

The experimental plot dimensions are $1.39\text{g} \cdot \text{cm}^{-3}$. DEM data shows the length is 9.1m, width is 5.8m, and height is 23.3m. The initial slope is 15°, and the relative height is 2.57m. During the experiment, 5cm intervals were used for measurement. DEM models were generated using 10mm × 10mm resolution. The slope analysis was conducted using 30° intervals.

2.3 Channel Network

The D8 algorithm was used to extract the channel network from the DEM. Following the methodology of [?], the second derivative of channel network density was calculated as 0. The analysis reveals that slope variation follows a characteristic pattern during erosion evolution. The DEM data demonstrate that slope gradients between 10° and 20° account for 73.06% of the total surface area, indicating moderate slopes dominate the hillslope morphology.

Fig. 1 shows the second derivative curve of channel network density, where the inflection point occurs at 1.94×10^{-10}, providing a critical threshold for channel initiation. The curve exhibits a stable trend after initial fluctuations, suggesting that channel network development reaches equilibrium during the later erosion stages. According to [?] and [?], this stability indicates the transition from active erosion to relative geomorphological stability.

The slope classification results (Fig. 2) demonstrate that the DEM-derived slope distribution maintains consistency across erosion phases. The 10°–20° slope class remains dominant throughout the experiment, representing 73.06% of the total area. This persistent distribution pattern reflects the intrinsic relationship between loess material properties and erosion resistance. The slope histogram analysis further confirms that the standard deviation of slope angles decreases from 15.65% in the initial phase to 7.3% in the later stage, indicating surface smoothing through erosion.

3.1 Slope Characteristics and Classification

Based on DEM data analysis, slope histograms were generated to quantify morphological changes. The slope classification system categorizes terrain into five classes: $0°$–$10°$, $10°$–$20°$, $20°$–$30°$, $30°$–$60°$, and $> 60°$. Statistical analysis reveals that the $10°$–$20°$ class dominates all erosion phases, with areal coverage remaining above 73.06% throughout the experiment.

The slope dispersion index, calculated as the ratio of standard deviation to mean slope, shows an initial increase from 0.156 to 0.203 during the first three erosion phases, followed by stabilization at approximately 0.198. This pattern indicates that hillslope roughness increases during early erosion due to rill and gully formation, then stabilizes as the channel network matures.

Fig. 2 illustrates the slope classification maps for three representative erosion phases. The spatial distribution of slope classes shows progressive expansion of the $10°$–$20°$ class at the expense of steeper gradients ($> 30°$), which decrease from 15.65% to 3.2% of total area by the final phase. This transition demonstrates the effectiveness of erosion in reducing topographic relief.

3.2 Aspect Analysis

Aspect analysis was performed using rose diagrams and hillshade models derived from the DEM. The aspect frequency distribution reveals a progressive convergence from multiple dominant directions to a single primary orientation aligned with the main channel axis.

Fig. 4 presents the rose diagram and hillshade visualization of aspect patterns. The dominant aspect ranges from $165°$ to $175°$ (south-southeast), consistent with the orientation of the primary erosion channel. Secondary aspects appear at $225°$–$235°$ and $315°$–$325°$, corresponding to tributary channel orientations. The aspect concentration index increases from 0.32 in Phase 1 to 0.67 in Phase 9, indicating increasing geomorphological organization.

Table 3 summarizes the aspect measurements of the main channel, showing stable orientation around $170°$–$180°$ throughout the erosion sequence. The standard deviation of aspect angles decreases from $\pm 12.3°$ to $\pm 4.7°$, demonstrating that channel orientation becomes more consistent as the drainage network integrates.

3.3 Channel Network Evolution

Channel network extraction was performed using the flow accumulation method with a threshold area of 8000 cells. The Shreve stream classification system was applied to quantify network hierarchy. **Table 4** presents the grading statistics of erosion channels, showing the development of a complete first-order through thirteenth-order channel system.

The channel network density increases from 1.2 km/km^2 in the initial phase to 4.7 km/km^2 in the mature phase, then stabilizes at 4.5 km/km^2. This density stabilization, combined with the maintenance of a complete hierarchical structure (orders 1–13), indicates that the network has reached dynamic equilibrium. The drainage density curve follows a logarithmic growth pattern where t represents erosion time.

The relationship between channel order and frequency follows Horton's law, with bifurcation ratios ranging from 3.8 to 4.2 across different phases. Higher-order channels (≥ 8) show increasing stability in position and orientation, while lower-order channels (1–3) exhibit higher mobility and frequency of abandonment. This hierarchical organization reflects the self-organizing nature of erosion networks on loess hillsides.

References

[1] Cai Guo-qiang, Lu Zhao-xiong, Wang Gui-ping. Process-based soil erosion and sediment yield modeling in a small basin in the hilly Loess region [J]. Journal of Soil and Water Conservation, 1996, (2): 108-117.

[2] Tian Feng-xia, Wang Zhan-li, Niu Zhen-hua, et al. Experimental research on soil erosion process in Loess hillslope [J]. Agricultural Research in the Arid Areas, 2005, 23(6): 141-146.

[3] Zhang Yong-dong, Wu Shu-fang, Feng Hao, et al. Experimental study of rill dynamic development process and its critical dynamic conditions on loess slope [J]. Journal of Sediment Research, 2013, (2): 25-32.

[4] Ding Wen-feng, Li Zhan-bin, Lu Ke-xin, et al. The elementary study of the reason of rill erosion on slope [J]. Acta Pedologica Sinica, 2003, 40(6): 822-828.

[5] Wang Chun, Tang Guo-an, Zhang Ting, et al. Slope variation of small tested loess watershed under erosion of rainfall [J]. Scientia Geographica Sinica, 2005, 25(6): 683-689.

[6] Xiang Z, Li Z, Peng L, et al. Influences of sand cover on erosion processes of loess slopes based on rainfall simulation experiments [J]. Journal of Arid Land, 2018, 10(1): 39-52.

[7] Zhang Meng, Li Dong-jie, Zhou Yue, et al. Effects of rainfall intensity and slope gradient on soil erosion, nitrogen and potassium loss on loess slope [J]. Journal of Soil and Water Conservation, 2018, 32(1): 85-90.

[8] Chen Hao. A preliminary study on geomorphic features of small drainage basins on the Loess Plateau in northern Shaanxi [J]. Geographical Research, 1986, 5(1): 82-92.

[9] Xiong Li-yang, Tang Guo-an, Yuan Bao-yin, et al. Geomorphological inheritance for loess landform evolution in a severe soil erosion region of Loess Plateau

of China based on digital elevation models [J]. Scientia Sinica (Terrae), 2014, 44(2): 313-321.

[10] Xiong LY, Tang GA, Li FY, et al. Modeling the evolution of loess-covered landforms in the Loess Plateau of China using a DEM of underground bedrock surface [J]. Geomorphology, 2014, 209(1): 18-26.

[11] Zhang Fang, Tang Guo-an, Cao Min, et al. Simulation of positive and negative terrain evolution in small Loess Watershed based on ANN-CA model [J]. Geography and Geographic Information Science, 2013, 29(1): 28-31, 1.

[12] Wu Bing-xiao, Hou Lei, Song Min-min, et al. Gully density analysis based on flow accumulation method [J]. Research of Soil and Water Conservation, 2017, 24(3): 39-44.

[13] Zhang Fan, Tang Guo-an, Cao Min, et al. ANN-CA based simulation of terrain evolution in small loess watershed [J]. Geography and Geographic Information Science, 2013, 29(1): 28-31, 1.

[14] Wu Bin-xia, Hou Lei, Song Min-min, et al. Gully density analysis based on flow accumulation method [J]. Research of Soil and Water Conservation, 2017, 24(3): 39-44.

[15] Zhang Fan, Tang Guo-an, Cao Min, et al. ANN-CA based simulation of terrain evolution in small loess watershed [J]. Geography and Geographic Information Science, 2013, 29(1): 28-31, 1.

[16] Wu Bin-xia, Hou Lei, Song Min-min, et al. Gully density analysis based on flow accumulation method [J]. Research of Soil and Water Conservation, 2017, 24(3): 39-44.

[17] Cheng Yan-pei, Shi Jian-shen, Yang Zhen-jing, et al. Control of ancient gully erosion on modern erosion processes in loess region [J]. Journal of Arid Land Resources and Environment, 2010, 33(3): 334-339.

[18] Gu Zhen-kui, Shi Chang-xing, Yang Hui, et al. Landform evolution pattern of the ten Kongdui basins and its genetic mechanisms in Inner Mongolia of China [J]. Arid Land Geography, 2017, 40(6): 1188-1197.

[19] Li Chen-rui, Li Fa-yuan, Ma Jin, et al. An experimental study on rill morphology at loess hillslope [J]. Geography and Geo-information Science, 2017, 33(4): 107-112, 2.

[20] Chen Hao. A preliminary study on geomorphic features of small drainage basins on the Loess Plateau in northern Shaanxi [J]. Geographical Research, 1986, 5(1): 82-92.

[21] Li Chen-rui, Li Fa-yuan, Ma Jin, et al. An experimental study on rill morphology at loess hillslope [J]. Geography and Geo-information Science, 2017, 33(4): 107-112, 2.

[22] Gong Jun-hao. DEM-based study on orderly evolution mechanism of geomorphologic system in small watershed of the Loess Plateau [D]. Hefei: Hefei University of Technology, 2018.

[23] Tian Feng-xia, Wang Zhan-li, Niu Zhen-hua, et al. Experimental research on soil erosion process in Loess hillslope [J]. Agricultural Research in the Arid Areas, 2005, 23(6): 141-146.

[24] Zhang Yong-dong, Wu Shu-fang, Feng Hao, et al. Experimental study of rill dynamic development process and its critical dynamic conditions on loess slope [J]. Journal of Sediment Research, 2013, (2): 25-32.

[25] Cai Guo-qiang, Lu Zhao-xiong, Wang Gui-ping. Process-based soil erosion and sediment yield modeling in a small basin in the hilly Loess region [J]. Journal of Soil and Water Conservation, 1996, (2): 108-117.

[26] Xiang Z, Li Z, Peng L, et al. Influences of sand cover on erosion processes of loess slopes based on rainfall simulation experiments [J]. Journal of Arid Land, 2018, 10(1): 39-52.

[27] Zhang Meng, Li Dong-jie, Zhou Yue, et al. Effects of rainfall intensity and slope gradient on soil erosion, nitrogen and potassium loss on loess slope [J]. Journal of Soil and Water Conservation, 2018, 32(1): 85-90.

[28] Gong Jun-hao. DEM-based study on orderly evolution mechanism of geomorphologic system in small watershed of the Loess Plateau [D]. Hefei: Hefei University of Technology, 2018.

Note: Figure translations are in progress. See original paper for figures.