Cyclic Steps in the Loess Plateau: Geometry and Physics

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Abstract. Cyclic steps form under various conditions and their geometry varies, but the physics that controls their geometry is poorly understood. This paper examines the geometry of cyclic steps in the Loess Plateau and explains the intrinsic physics that control their geometry. The data of cyclic steps in gullies from two small basins in the Loess Plateau, China, was collected and we compared this data with existing field and lab datasets. Our field data shows that step length and the ratio of step length to step height decreases with increasing mean channel slope. However, step height itself does not significantly correlate with mean channel slope. Through comparison with other datasets, we find that a less erodible bed develops a smaller ratio of step length to step height, a result confirmed by a theoretical model. We also propose that step length adjusts to dissipate energy, forming a stable system of cyclic steps.

Keywords: Cyclic steps; Geometric features; Bed erodibility; Energy dissipation; Theoretical model

1 Introduction

Cyclic steps are bedforms commonly occurring in steep channels, and they have been documented in various environments including flows in alluvial streams, bedrock or gravel bed streams and submarine flows related to turbidity currents[5][9]. Their origin is related to the instability of shallow Froude-supercritical flow over an erodible bed[7]. Each step consists of a sharp transition in channel bed slope from a shallowly-sloped sub-critical zone to a rather steep super-critical zone. Internal hydraulic jumps connect the reaches of super-critical and sub-critical and steps migrate upstream[5]. The development of bed steps changes the process of water flow and sediment transport, playing an important regulatory role in soil erosion. Understanding the evolution law of bed

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steps is of great significance for predicting bed friction and sediment transport rates in steep gullies with bed steps.

Until now, cyclic step geometry has been investigated by many researchers at both field and at laboratory scale[3, 4, 8, 10, 11]. Cyclic steps form under various conditions and their geometry varies, but the physics that controls their geometry is poorly understood. Loess has special properties that distinguish it from other bed materials, and the periodic step morphology may also exhibit specificity. However, there is currently a lack of data on the periodic step morphology of loess, and the understanding of step morphology in loess is not yet sufficient. In order to address those gaps above, we describe cyclic steps in the Loess Plateau, China, where the channel bed is made of weakly-cohesive silty loess that readily collapses when wet. When the easily-suspended material is eroded, it acts as a washload; it is assumed that eroded sediments are not deposited again within the domain, so we neglect deposition and consider these cyclic steps to be purely erosional.

The objective of this paper is to identify the geometry of cyclic steps in the Loess Plateau and the potential physics that controls their geometry.

2 Field Area and Methods

Our study sites include two small basins, Qiaogou basin and Wangmaogou basin, in the Loess Plateau, which are characterized by a typical monsoon climate with distinct flood season (usually from June to August). Both basins have steep gullies with cyclic steps, and gully morphodynamics are dominated by migrating cyclic steps. Qiaogou basin is less affected by human interference, but in Wangmaogou basin many check dams control the downstream boundaries of gully evolution. The gullies in the study sites are steep and narrow and the bed material is weakly-cohesive silty loess. During the field survey, there was no flow in the gullies, and the bed was covered with sparse grass and small bushes.

We used Real-Time Kinematic (RTK) GPS to survey the gullies. Real-Time Kinematic (RTK) GPS, which is one of the mature technologies for river terrain measurement, has been widely used in field survey and its measurement accuracy can reach centimeter level. Mean channel slope, mean step length, and mean step height were extracted from the bed profiles. By using the method of Parker and Izumi (2000)[7], step length is defined by the horizontal distance from the start to the end of each step and step height is defined by the vertical height of the steep part of a step (Fig. 1). We also measured step width that is defined by the channel width at the slope transition from a gentle-sloped zone to a rather steep zone, as well as and the grain size distribution along the channel.

In addition to this field data, for comparison we collated datasets of purely-erosional cyclic steps at field and laboratory scales, including three datasets from lab experiments of cohesive beds[2, 3, 6] and two field datasets in bedrock and gravel beds[8, 10]. Data comparison allows us to analyze the similarities and differences of cyclic step geometry among different conditions.

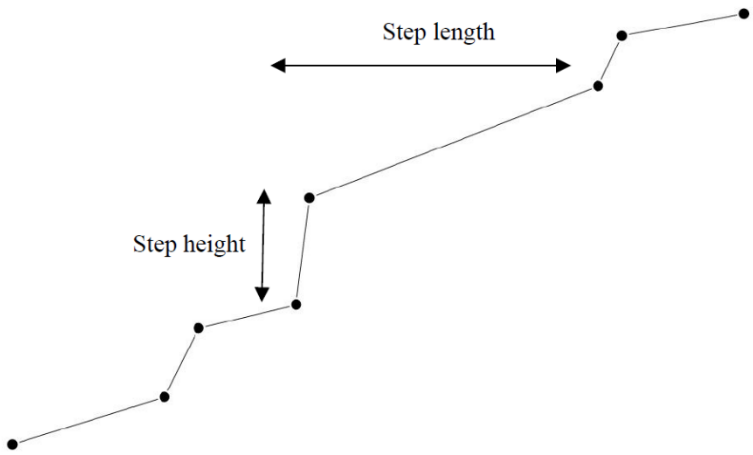


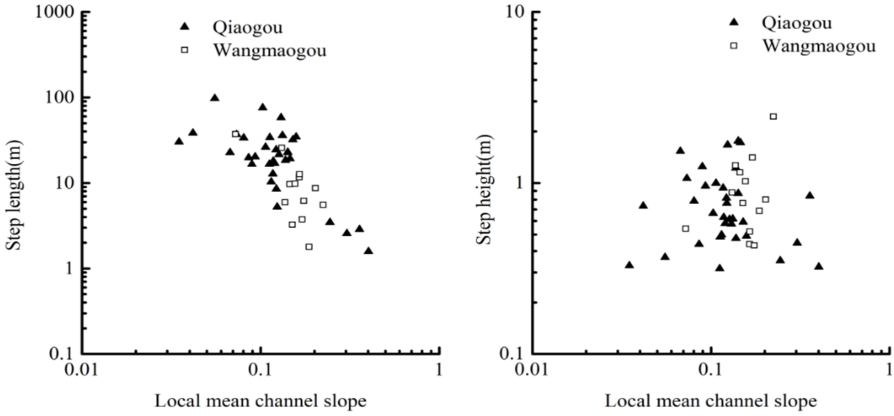
Fig. 1. Definitions of step length and step height.

3 Data Analysis

Fig. 2(a) relates measured step length from both basins against the local mean channel slope, which is defined by the bed slope of the center point of each step based on the mean bed profile obtained by fitting the field data we got. Step length decreases with increasing local mean channel slope up to a mean channel slope of 0.25; beyond this value, step length remains almost constant. Step height is plotted against local mean channel slope in Fig. 2(b). The plot shows that there is no significant correlation between step height and local mean channel slope. Furthermore, step length and step height do not correlate with step width (Fig. 3). Additionally, step aspect ratio, defined as the ratio of step length to step height decreases with increasing local mean channel slope (Fig. 4(a)).

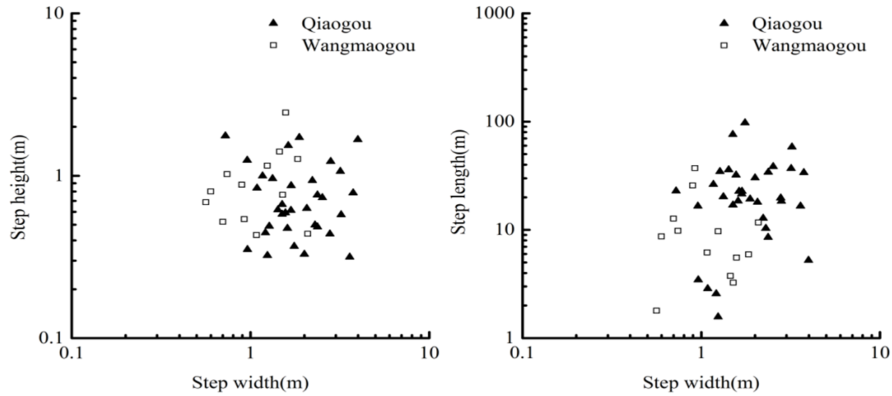
Comparing this with the datasets of purely-erosional cyclic steps, all datasets show that step aspect ratio decreases with increasing mean channel slope. Field and laboratory datasets are separated into Fig. 4(a) and Fig. 4(b) respectively. Cyclic steps in both Qiaogou and Wangmaogou basin have a larger step aspect ratio (at common slope values) than the other field datasets. Comparing three datasets from laboratory experiments[2,3,6], the step aspect ratio of Brooks (2001)[3] is smaller than other two datasets.

Brooks (2001)[3] proposed that the bed substrate composition affects bed erodibility and therefore also step aspect ratio. However, there is no sufficient evidence to prove the hypothesis. The bed material of Brook's experiments has the lowest overall erodibility of the three lab datasets. Field bedrock and gravel beds may have an even lower bed erodibility and lower erosion rate compared to the channel beds in the Loess Plateau. Based on the previous data analyses, step aspect ratio is thought to become smaller as bed erodibility decreases. Thus, we can further hypothesize that lower bed erodibility leads to a smaller step aspect ratio. More evidence regarding how bed erodibility affects cyclic step geometry is provided in the discussion.



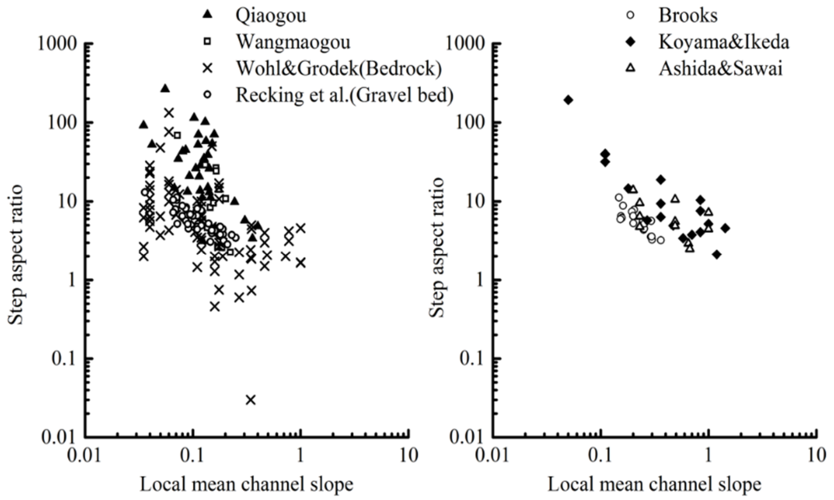
(a) (b)

Fig. 2. Data collected from Loess Plateau Qiaogou and Wangmaogou basins. (a) Step length against local mean channel slope. (b) Step height against local mean channel slope.



(a) (b)

Fig. 3. Data collected from Loess Plateau Qiaogou and Wangmaogou Basins. (a) Step height against step width. (b) Step aspect ratio against local mean channel slope.



(a) (b)

Fig. 4. Cyclic Step dimensions in purely-erosional field (a) and lab (b) settings. Both figures compare step aspect ratio against local mean channel slope.

4 Discussion

4.1 Effect of Bed Erodibility on Step Aspect Ratio

To assess the hypothesis that bed substrate composition will influence cyclic step geometry, the general form of bed erosion equation[7] for cohesive sediment is adopted as shown in Eq. (1),

$$E = \alpha \left(\frac{u^2}{u_t^2} - 1 \right)^n \tag{1}$$

where E is the dimensionless sediment entrainment rate, α is a scaling coefficient, u is depth-averaged flow velocity, u_t is the threshold velocity for erosion, and n is a rate exponent.

Here we study the ratio of step length to step height under different values of the threshold velocity u_t and exponent n using the theoretical model of Parker and Izumi (2000)[7]. The model predicts cyclic step geometry in the quasi-permanent upstream-migrating state. When the bed resistance coefficient and flow discharge are specified, two Froude numbers, Fr_t and Fr_n, as well as exponent n of the bed erosion relation determine cyclic step geometry. Fr_t is the Froude number related to the threshold velocity u_t, so changing Fr_t is equivalent to changing the threshold velocity u_t. Fr_n is the Froude number related to normal flow in the absence of steps, which can be regarded as the analog of mean channel slope. Here, we change Fr_n, Fr_t and exponent n to determine step geometry. The model provides dimensionless parameters such as dimensionless step length L, dimensionless step height H and the Froude number Fr_n. We then scaled to dimensional parameters. Dimensionless step length L is defined by the dimensionless horizontal distance from the start to the end of a step, and dimensionless step height H is defined by the dimensionless maximum vertical distance of a step from the downstream end. Eq. (2) gives the method by which dimensionless variables are scaled to dimensional variables,

$$L_d = \frac{q_w}{C_f Fr_t^2 u_t} L \quad H_d = \frac{q_w}{u_t} H \qquad \frac{L_d}{H_d} = \frac{1}{C_f Fr_t^2}\frac{L}{H} \qquad S = C_f Fr_n^2 \tag{2}$$

where q_w is the water discharge per width, C_f is the bed resistance coefficient, L_d is dimensional step length, H_d is dimensional step height, and S is the mean channel slope. The bed resistance coefficient and flow discharge are held constant in all the runs. The ratio of dimensioned step length, L_d, to dimensioned step height H_d, denoted by L_d/H_d, is scaled by the dimensionless step length over height L/H divided by Fr_t^2. As previously noted, the mean channel slope can be scaled by Fr_n^2. We plot $L/H/Fr_t^2$ versus Fr_n^2 to represent the plot of L_d/H_d versus the mean channel slope. As shown in Fig.5, the exponent n has little effect on step aspect ratio, but increasing Fr_t leads to a smaller step aspect ratio. A larger Fr_t relates to a lower bed erodibility and the bed becomes harder to be erode. Thus, we can draw the conclusion that step aspect ratio decreases for a less erodible bed.

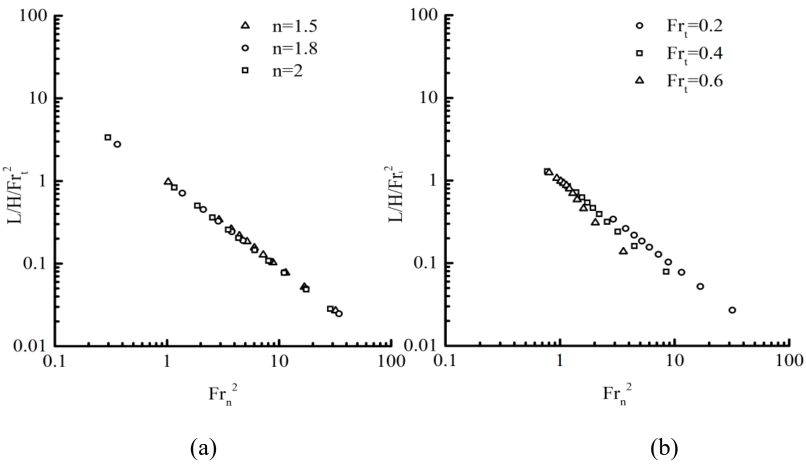


Fig. 5. (a) The effect of varied n on step length over step height. (b) The effect of varied Fr_t on step length over step height.

4.2 Hypotheses to Explain Why Channel Average Slope Controls Step Length But Not Step Height

Steps in step-pool systems tend to maximize bed resistance to stabilize the system [1]. Step-pools are bed steps of cobbles, boulders, bedrock or woody debris with alternating pools with fine sediment[8]. The essential difference between cyclic steps and step-pools is that the substrate of cyclic steps can be incised but the substrate of step-pools is not exposed at all[3]. Cyclic steps are closely related to step-pools and we hypothesize that they develop the similar function of energy dissipation. Cyclic steps dissipate energy through spatially alternating internal hydraulic jumps. According to the theory of Parker and Izumi (2000)[7], the energy loss of a hydraulic jump depends on the erodibility of the substrate and flow discharge. The substrate affects the efficiency of energy dissipation by adjusting the step geometry. The bed slope influences the flow structure and also the pattern of energy dissipation. In order to keep the system stable, a larger bed slope requires more energy dissipation, which is accomplished through more, shorter steps. Therefore, the mean channel slope is a good proxy of step length. This hypothesis requires testing using data from laboratory experiments, and analytical or numerical simulations.

The theory of Parker and Izumi (2000)[7] illustrates that step height decreases with increasing mean channel slope in the equilibrium state. However, there is no apparent relationship between step height and channel average slope in the field data. One possible explanation is that cyclic steps take sufficiently long to equilibrium state and the step height is still in adjustment. Besides that, the variation of bed resistance in space also leads to a poor relationship between step height and slope. These ideas must be elaborated upon in the future work.

5 Conclusions

Average channel bed slope is a good predictor for cyclic step geometry. Step length decreases with increasing mean channel slope but step height does not correlate with slope. However, in this study, the understanding of the reason that channel average slope controls step length, but not step height is not yet sufficient. We hypothesize that the relation between step length and mean channel slope in cohesive beds is related to the adjustment of energy dissipation but this hypothesis has not been confirmed. In the future, the lab experiments or numerical runs of bed step evolution under different inflow energy at a fixed initial channel bed slope can be conducted to confirm the hypothesis.

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