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◆Research Paper◆

Study on the Small Gravity Erosion on the Gully Slopes

YANG Jishan[1]
1.*Yellow River Institute of Hydraulic Research, Zhengzhou，450003, China*

Abstract: Gravity erosion is active in the hilly-gully region of Loess Plateau which contributes large amount of sediment by conveying much earth into the valleys. Field observation on the gravity erosion was carried out in Qiaogou watershed. Erosion pins were used to measure erosion rate on the gully slope, and shear tests were done to discuss the effecting factors of the gravity erosion. Field survey showed that mainly small gravity erosions were occurred in Qiaogou watershed and which produce much sediment. Three types of small gravity erosion types, including loess grain fall, mass fall and slump, were measured, and their effecting factors were discussed. Study shows that the small gravity erosion are mainly controlled by the slope gradient, rainfall, weathering, etc. These influence factors can reduce the internal friction angle and cohesion of the intact loess and therefore lead to lowering the critical depth of the gravity erosion on the slope, this can explain the occurrence of the shallow gravity erosions on the slopes. Gravity erosion has different intensity in different evolution stages of the gully, so it is possible to estimate the intensity of gravity erosion by the evolution stages of the gully.

Keywords: Gravity erosion, Loess Plateau, Gully slope, Valley evolution, Erosion pin

1 Introduction

Gravity erosion on the loess slope is the result of potential gravity energy release of the earth as the topographic uplifting, but it is also an important agent in the process of valley evolution on the Loess Plateau. Macro-characteristics of the valley such as slope gradient and depth are mainly determined by the material nature and crust uplift height, but the micro-topography features of which is normally shaped by the actions of hydraulic and gravity erosion (Korup and Densmore, 2010). With the semi-arid climate, water, gravity and wind are the three main agents of erosion in the hilly-gully region of Loess Plateau. Although hydraulic erosion may be still the dominant force in forming valley landscape, gravity erosion is very active in the process, especially on the steep slopes as the weak consolidation of the loess in the region.

Gravity erosion contributes large amount of sediment yield by conveying much soil into the valleys directly or indirectly. For example, according to the field data provided by the Yellow River Conservancy Commission (1993) observed in three watersheds on the Loess Plateau, namely Nanxiaohe gully, Luer gully, and Jiuyuan gully, the ratios of sediment produced by gravity erosion to the total soil loss were about 57.5%, 68.0% and 20.2%, respectively. Some studies based on the field observation data showed that gravity erosion is always an important source of sediment in the water flow from slope to the valley, and it may be responsible for the occurrence of high frequency of the hyperconcentrated flows on the Loess Plateau (Wang X. K., et al，1982； Xu J. X., 2004a, 2004b；Han P., et al, 2003).

Many researches have been done on the problem of gravity erosion. More researches have focused on the general classification and the intensity distribution of gravity on the Loess Plateau (Zhu T. X. et al, 1989, 1990; Cai Q. G., 1993; Liu B. Z. and Wu F. Q., 1993). Zhang X. B.，et al (1989) analyzed the relationship between gravity intensity and the specific sediment yield. Wang G. Q., et al (2005) established a theoretical model to calculate the probability of the gravity erosion on the gully slope. Ye H., et al. (2006) tried to monitor the retreating speed of the valley edge line as gravity erosion by GPS, etc. In the overall sense we fell that most researches on the gravity erosion are still focused on the qualitative description and qualitative analysis mainly because the complexity of the phenomenon and the lack of field observation data.

2 Study area

Qiaogou watershed, being located in Suide Country, Shanxi Province (about 37°30′*N*, 110°18′*E*), is a tertiary order tributary of the Yellow River. It drains an area of about 0.45 km^2 with an elevation range of about 900~990m. Qiaogou watershed is composed of a main channel and two branches. The main channel length is about 1.4 km, the first branch has a length about 870m and area of about 0.069 km^2, and the second branch has a length about 870m and area of about 0.069 km^2 (figure 1).

Qiaogou basin situates the typical hilly-gully landscape area of the Loess Plateau, and it has the typical structure and figure of that region. Slopes of Qiaogou gully can be conceptually divided into two parts by the gully-edge line, namely the hill and the valley (figure 2). The hill top is characterized by a gentle slope of 0~10° and high shrub cover, the hill slope commonly has a gradient about 30° and high grass cover, while the gully slope is often >40° and with a very sparse herbage cover. The bottom of the valley is the place where temporary water is concentrated.

The loess mantle depth in the study area is about 60m, which is mainly consisted of two types of loess. The upper layer of the earth is Malan loess, and the lower layer of which is Lishi loess. Malan loess contains about 5% of clay (<0.001mm), 30% of fine silt (0.001~0.01mm), 46% of silt (0.01~0.05mm), 19% of sand (>0.05mm), while the Lishi loess contains about 7% of clay, 24% of fine silt, 57% of silt, 12% of sand.

The region of Qiaogou catchment has a continental semi-arid climate, with an average annual temperature of 8°C. The average annual precipitation of the region is about 450mm, usually 70% of which occurred mainly in mid-June to mid-September.

Figure 1 Drainage Structure of the Qiaogou catchment

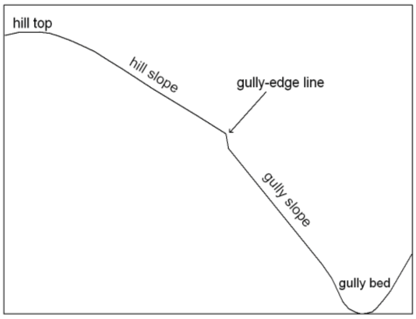

Figure 2 Sketch map of the cross-section of slope structure from hill top to gully bed in Qiaogou catchment

3 Methods

The data used in this paper were measured with erosion pins and survey in Sept. 2009 to Sept. 2011. The steel erosion pin is about 35cm long and 3mm in diameter. A total of about 300 erosion pins were installed on the gully slopes of the second branches of the Qiaogou gully. Exposure lengths of pins were measured in March and September every year. The erosion pins can only used to measure very shallow gravity erosion types, such as loess grain fall, small fall, shallow slump, etc. Field survey along the gully was done to observe and measure bigger gravity erosion after heavy rain because they mainly occur during or after heavy rain time in the summer and autumn seasons.

Undisturbed soil samples of the Malan and Lishi loess were gotten in the study area. Particle size analysis was done with laser particle size instrument, and shear strengths of the two types of loess with different water content were measured by direct shear tests. Four types of soil sample were made with the water content of 7%, 13%, 19% and 25%, respectively. The sample of water content of 7% roughly equivalent to the drought situation, 13% represents to the semi-wet state, 19% represents the wet condition, and 25% is close to the state of water saturation state.

4 Results and discussion

Field survey showed that many types and sizes of gravity erosion occurred in the Qiaogou basin, but most of which were small types, rarely large ones. Small gravity erosion occurred with high frequency, and it had great influence on the sediment yield in the watershed. During the survey period, only the small gravity erosion types, containing 112 times of including loess grain falls, 28 times of small mass falls, and 14 times of small slumps, were observed. No landslides or other large gravity erosions were observed.

(1) Loess grain fall

Loess grain fall is the phenomenon of sudden displacement of the loess grain or very small fragment by rolling down the steep slope. It is the most common and smallest size type of gravity erosion on the loess slope. During the time the new undisturbed loess is exposed to the air, cohesion is gradually lost because of weathering, and this is main reason of the occurrence of loess grain fall. This phenomenon can take place at any time in the year, but especially in spring and after rain time.

The data obtained by erosion pins show that erosion depth of loess grain fall on the slopes is considerable scattered (figure 3). In all the points, about 25% were near zero, 60% within 1 cm, and about 15% between 1~2 cm. Loess grain fall occurs mainly on the steep slopes more than 55°, especially on the slopes between 65° ~ 80°. The phenomenon of small loess grains rolling down slope may have close relation with the static friction angle of loess, which is about 55°. So, loess grain fall mainly occurs at gradient more than 55°, the slope is steeper, the easier it happened. In addition, loess weathering on the slope of 55° ~ 80° is severest, so it is most likely to happen at that gradient. Slope of more than 80° has a small rain-receiving area and slighter weathering degree, so loess grain fall at that gradient is weaker. Loess weathering on the shady slopes is weaker than that on the sunny slopes, so loess grain fall on the sunny slopes is much more remarkable. According to the observation data, average retreating rate caused by the loess grain falls on the slope more than 55° is about 2.0 mm/a on the sunny slope, and about 0.9 mm/a on shady slope. Then we can estimate that sediment produced by loess grain fall in Qiaogou's second branch is about 3.2 t/y. Considering the catchment area of the second branch, that is equivalent to the specific sediment yield of 450t/km^2·a.

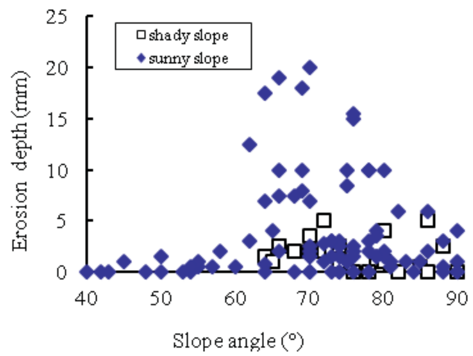

Figure 3 Distribution of the erosion depth by loess grain fall with the slope angle

(2) Mass fall

Mass fall of the loess indicates the phenomenon of small blocks and fragments of loess fall from the steep slope face usually separately. The mass falls always derived from a very narrow superficial part of the loess slope, so the size is usually very small (figure 4). Loess mass falls mainly occur on the slopes more than 60°, especially on the slopes at 65°~ 85°. A single mass fall is about 10^{-5} ~ 0.1 m^3 in volume. Similar to the loess grain fall, weathering also plays an important role in the process of loess mass fall. Field observation shows that it generally has three groups of joint-plane on the loess slope surface which breaks the intact loess into small pieces. So, under the condition of cyclical changes of temperature and humidity, frequency of the small loess mass fall is high. Although it is difficult to accurately estimate the material produced by mass fall from the slope, according to observation, it may be of the same order of magnitude as the loess grain fall.

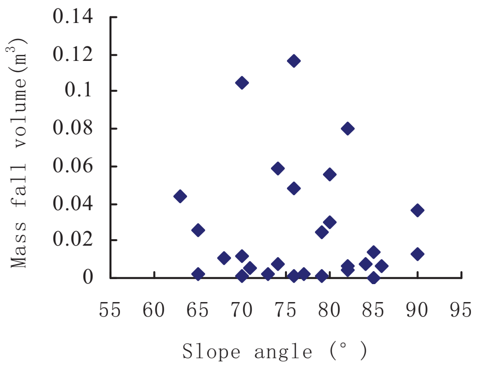

Figure 4 Distribution of the loess mass fall size with slope angle

(3)Slump

Slump is the loess downward sliding along the shear plane in the slope. Scales of slump obtained in Qiaogou in the survey period were approximately between 0.3 m^3~3.5 m^3 (figure 5). Among them, magnitude of <1 m^3 occupies most proportion, and the part of >1 m^3 occupies a less proportion. Most slumps occur on the slopes at 60° ~ 80°, especially on the slope at 70° ~ 80°. According to observation, the slump bodies generally possess a wedge-shaped outline. Angles of the sliding planes usually reduce 10° ~ 20° than that of the original slope, and the angle of sliding planes are generally remained more than 50°. Slump generally develops along the loess joint, and it is often happened after rainfall, rarely takes place in the dry season. Rainfall and soil weathering is the main triggering factors of loess slump.

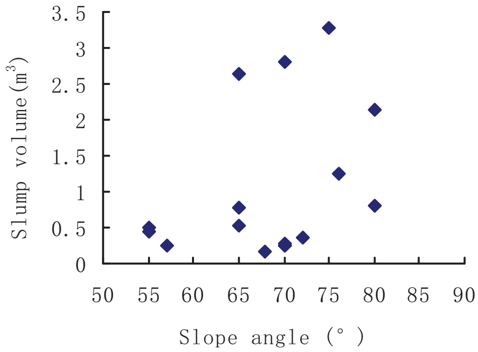

Figure 5 Distribution of the slump size with slope angle

5 Mechanism Analuses

The stability of a slope is determined by the relationship of the shear strength resisting the slide and the shear stress acting to induce movement. If there is a potential sliding surface in the loess, considering the simplest factors, shear stress (τ) along the potential sliding surface can be given by

$$\tau = \gamma h \sin\beta \tag{1}$$

Where γ is the unit weight of loess, h is the average thickness of the sliding mass, β is angle of the sliding plane.

Shear strength (τ_f) can be given by

$$\tau_f = \gamma h \cos\beta tg\varphi + c \tag{2}$$

Where φ is the angle of internal friction, c is cohesion.

When gravity erosion happens, it meets the following condition

$$\tau / \tau_f \geq 1 \tag{3}$$

From function (1) and (2) we can see that shear stress (τ) depends primarily on the downslope component of the weight force, while shear strength (τ_f) is mainly provided by the forces of friction and cohesive of the material. The influence factors mainly includes β, c, and h, etc., in which β and c can be changed by the environmental variables significantly and thus affect the slope stability. They also show that τ changes little with time and environmental changes, while τ_f may experiences a gradual reduction as the process of weathering.

Shear tests of the Malan loess and Lishi loess shows that c and β decline significantly with the increase of water content (Figure 7, Figure 8).

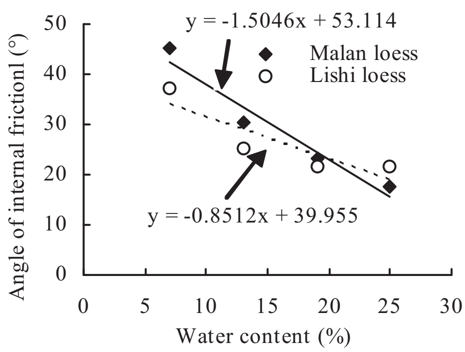

Figure 6 Relationships between angle of internal friction and water content

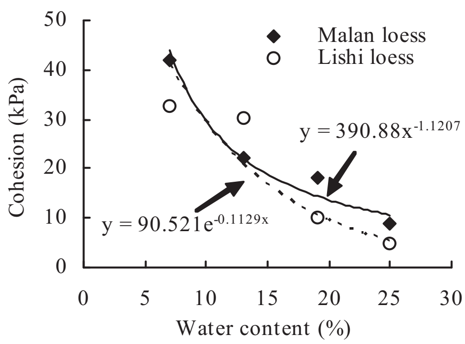

Figure7 Relationships between cohesion and water content

Decline of c is the direct cause of small mass failure on the loess slope, especially to the occurrence of loess grain fall, small mass fall, etc. Rainfall falls c and increases weight of the loess mass (γh), and thus causes stripping of the weathered loess on steep slope. In addition, the process of the intact loess being fractured into debris as weathering also leads to losing of cohesive force. Therefore, loess grain falls and small mass falls always take place on the highly weathered loess slope, and the freeze-thaw, dry-wet circulations can often lead to the occurrence of such kinds of small gravity erosions.

Occurrence of slump has a close relation with the decrease of c and β of the loess. Angle of internal friction of the loess is about 20°~ 40°, while slump usually occurs on the slope of 55° ~ 80° (figure 5). So, once c and β decrease, slump would be easily to occur. Slumps often occur along the joint planes after rainfall. Field measurements in the Qiaogou catchment show that slumps often happen when water content reach 12% ~15% for the Malan and Lishi loess, and the internal friction angle of the loess is about 25° ~35° at this stage. According to equation (3) and the shape of the slipping mass, we can get that cohesion at the slip plane is generally less than 5kPa, whereas the tested value of cohesion is about 25kPa in intact loess with the same water content (figure 7). This shows weathering and joins in the loess play important roles in the occurrence of slump.

Gravity erosion depth (h) have important influence to slump. With the process of downward erosion in the channel, weight of the loess above the potential slipping plane will continually increase, and it may exceed shear resistance and trigger occurrence of frequent deep-seated landslides, which means the valley has reached the critical depth. The critical depth of the valley can be calculated by the following formula (Korup and Densmore, 2010)

$$H_c = \frac{4c \sin\theta \cos\varphi}{\gamma[1-\cos(\theta-\varphi)]} \tag{4}$$

Where θ is slope angle.

By using equation (4) with c =30kPa, ρ=1.6g/cm^3, θ=45°, φ=30°, we can get the critical depth is about 57.9 m in Qiaogou basin, which is close to the depth of the first branch of the Qiaogou gully (about 50m). But obviously, large landslides or landslips have never been seen there. This is because consolidation strength of the intact loess performs large cohesive force, but it is not contained in equation (4). In fact, many loess gully walls can often reach to the height of about one hundred meters in the Loess Plateau.

Relationships of h, φ and c can be represented in figure 8. It shows that the value of H_c decreases significantly with the reduction of c and φ. The environmental factors of weathering, cracks, joints, rainwater, etc. can make the shallow gravity erosions take place in a relatively shallow depth. Kevin's (1995) study at Washington and California showed that cohesion and angle of internal friction can be reduced to very low levels in the loose debris, this perhaps can interpret the occurrence of the shallow slumps happened in the Qiaogou watershed.

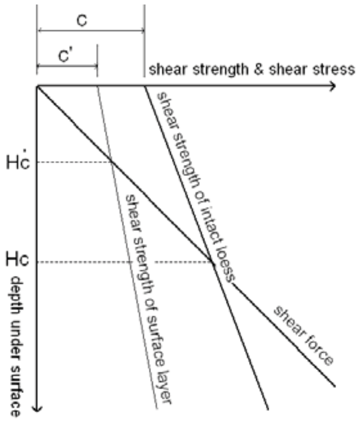

Figure 8 Changes in critical depth of gravity erosion with cohesion and internal fraction angle

c is cohesion of intact loess, c′ is cohesion of the weathered surface layer loess, Hc is critical depth of the intact loess, Hc′ is critical depth of the surface layer loess

6 Coupling relationship of slope process and gravity erosion

The two branches of Qiaogou gully are in different stages (figure 9). The firs branch is in the young and unstable stage, with a V-shaped cross section. Width of the first branch is only 1~2 m at the bottom, but its depth has reached about 50 meters. Gully slope of the first branch is very steep, usually more than 55°, as the action of deep-cutting in it is very severe. Many scars of gravity erosion are visible on the gully slopes, showing the mass failure is active in the first branch. Though having no exact measured data, we can estimate from observation that more than half of the sediment yield in the gully are produced by gravity erosion.

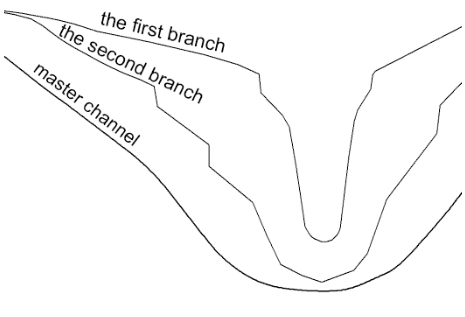

Figure 9 Cross-sections of the master channel and two branches of Qiaogou gully

The second branch is a middle-aged gully with a U-shaped cross section. After a long period of adjustment, the width of the gully reaches about 5~15 m at the bottom, and gradient of the gully slope is about 40°~55°. With the gully slope gradient decreasing, hydraulic erosion is enhanced and gravity erosion is weakened. We can see that terrace terrain is shaped on the gully slopes of the second branch under the compositive effects of hydraulic and gravitational erosion. Two levels of terrace on the shady gully slope and about five levels of which on the sunny gully slope are formed. The nearly vertical terraces have the height o about 1 m ~ 7 m, where are the main regions for occurrence of the gravity erosion. Usually, a straight slope is below the terrace face, where is the depositional place of the sediment coming from the terrace face by gravity and hydraulic erosion. Thus, the straight slope under the terrace can be termed "gravity slope" here. The gravity slope is the delivery route of the sediment produced from the upper terraces, and it is an equilibrium transportation slope on which equal quantities of earth are being supplied and removed.

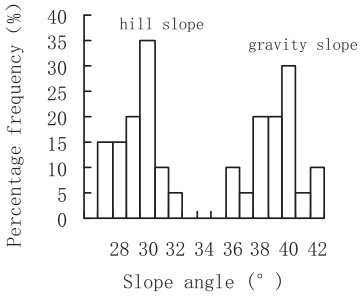

Figure 10 Distribution of the angles of hill slopes and gravity slopes on Qiaogou catchment

Slope form can reflect the relative relationships of soil erosion, transport and deposition processes. Profile of the upper hill slope is convex, while the lower part of the hill slope is generally straight at about 30°, and the gravity slope is generally straight at about 40°. We measured randomly 20 of gravity slopws and hill slopes respectively, and the percentage frequency of the slope angles are shown in figure 10. Field observation shows that hill slopes have no soil layer, which indicates a weathering-limited erosion process on the slope, and flow on the slope is generally unsaturated of sediment concentration. Obviously, the gravity slope is formed because the sediment supply from upper slope exceeds sediment transport capacity of the slope flow.

Sediment transport capacity of the overland flow can be calculated by the following formula (Julien, 1985)

$$q_s = aS^b q^d i^f (1 - \frac{\tau_{cr}}{\tau})^k \quad (5)$$

q_s is unit sediment transport capacity, S is slope angle, q is unit discharge, i is rain intensity, τ is shear stress, τ_{cr} is critical shear stress, a, b, d, f k is coefficient, and b =1.2~1.9, d =1.4~2.4.

Using this equation, we can compare sediment carrying capacity of water on the hill slope with that on the gravity slope. If considering the difference of slope gradient only, and taking $b = 1.5$, using (5), we can get that sediment transport capacity on the gravity slope is 1.75 times higher than that on the hill slope. Thus we can estimate that sediment coming from the gravity erosion on the terrace account for more than 42% of the total sediment yield on the whole slope.

7 Conclusions

(1) Many types of gravity erosion take place in the Qiaogou drainage basin, but they are usually small in volume, such as loess grain fall, small mass fall, small slump, etc. These small and shallow gravity erosions commonly occur on the basis of weathering of the intact loess. The influence factors consist of slope gradient, rainfall, weathering, etc., this make the small gravity has the character of high randomness.

(2) Small gravity erosion mainly takes place on the slope more than 55°, but the correlations of size and frequency of the small gravity with slope angle are scattered. The depth of small slump occurs in roughly the same depth with rainfall infiltration, it generally happened along the joints in the shallow loess slope. Rainfall and weathering reduce the cohesion force and internal friction angle of the loess, thus reducing the critical depth of gravity erosion occurring. This is the main reason for the slump occurrence.

(3) Gravity erosion is an important agent in the process of valley development. Gravity erosion has different intensity in different evolution stages of the gully, so it is possible to estimate the intensity of gravity erosion by the evolution stages of the gully.

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