A SCALE MODEL EXPERIMENT ON RELATIVE STABILITY OF CHECK-DAMS IN THE LOESS PLATEAU, CHINA

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Abstract

This paper presents an experimental method in the laboratory to evaluate and prove the relative stability of check-dams. The term relative stability of check-dams means the check-dam needs not be heightened or the workload for heightening the dam could be afforded by the local people for the dam-land area grows and becomes so large that the mean dam-land elevation and mean slope gradient keep almost constant. A scale model experiment was conducted to demonstrate the condition and mechanism for the relative stability of check-dams, which developed sequence dependent relationships between mean slope gradient, mean dam-land elevation, and the dam-land area. Check-dam system is the most effective measure to conserve soil and water on Loess Plateau, China. In the design and construction of check-dam systems, elements such as layout of the dam-sites, height of the dams and the controlled area of the small watershed all should meet the standard for relative stability. Relative stability of check-dams is generally studied by field investigation. In contrast, a scale model experiment in the laboratory is introduced in this study.

Additional Keywords: landform, gully erosion, scale model experiment, loess plateau

Introduction

The Loess Mesa Ravine Region and the Loess Hill Ravine Region, which covers 200000 km^2 in area of the Loess Plateau in China, are seriously attacked by soil and water erosion. The most effective way to conserve soil and water in these areas is to build up check-dam systems in gullies. At present, more than 100000 check-dams have been built and the amount of sediment retained by check-dams is the largest in all measures (Xu. *et al*., 2004). However, in the design and construction of check-dam systems, elements such as layout of the dam-sites, height of the dams and the controlled area of the small watershed all should meet the standard for relative stability. Inspired by the natural Juqiu, a kind of dam-land resulting from a land-slip which never overflows when impounding the floodwater and soil for centuries, people came to recognize the important role of dam height and the ratio of dam-land area to that of the controlled watershed. It was observed that if the above parameters reached a certain value, soil and water in the small watershed could be internally absorbed without raising the height of the dam. In 1960s, the concept of *relative stability of the check-dam system* emerged, which stemmed from the recognition of the key factors that determined the natural balance of check-dams. Relative stability of check-dams is generally studied by field investigation (Fang, 1995 & 1998; Zeng, *et al*., 1995 & 1999; Lei and Zhu, 2000). In contrast, this paper presents an experimental method in the laboratory to evaluate the stability of check-dams, and proves the possibility of relative stability for check-dams by a scale model experiment.

Background

The rate of gully incision is controlled by water flow velocity, depth, turbulence, temperature, and by soil texture, soil mechanical pattern, level of protection by vegetation (Sidorchuk, 1999). Gullies erode downwards until a layer of low susceptibility to erosion is reached, after which they widen and the erosion rate decreases. Eventually the gullies “equilibrate” with the overland flow (Foster, 1982). Novak (1985) developed physically-based equations to calculate the time required to reach equilibrium for rill and channel erosion. Recent research indicates that gully formation could be divided into two stages (Sidorchuk, 1999). It is very rapid during the period of gully initiation, when morphological characteristics of gully (length, depth, width, area, and volume) are far from stable, which is very short, about 5% of a gully’s lifetime. For most part of a gully’s lifetime, its size is near stable, maximum value. At the first stage of gully initiation, hydraulic erosion is predominant at the gully bottom and rapid mass movement occurs on the gully sides. At the last stage of the stable gully, sediment transport and sedimentation are the main processes at the gully bottom; its width increases due to lateral erosion, and slow mass movement transforms the gully sides. Where the local conditions permit, some streams have retained relatively stable channel patterns over a period of more than a century, despite a history of major floods (Jeff, 2002; McEwen, 1994; Warburton et al., 1993).

As check-dams have been built in the small watershed on the Loess Plateau, relief of the gully is changed. Substantive sediment caused by rainfall and flood is stored in the dam-land for decades and the mean slope gradient of the gully becomes gentle. Consequently erosion in the gully keeps on alleviating and the gully becomes relative stabilization at last. On the other hand, even though the amount of sediment from upper reaches is not reduced, rise velocity of the dam-land becomes slower due to the enlargement of the dam-land area. Hence a critical height of check-dam exists in the given gully with the definite condition of soil and water, geology and physiognomy. If the check-dam in the gully were higher than that value, with deposition in front of the check-dam, the mean slope gradient of the gully would be gentle enough to decrease the erosion greatly. As a result, for annual sedimentation thickness is very little in the late age of forming dam-land, the workload for heightening the dam is so little that local people could afford it (Zeng, 1999). Despite other aspects are included in the relative stability of check-dam system (Fang, 1995), equilibrium of soil and water in the gully is the most important criterion all the while.

It is completely possible for the dam systems to become relatively stable. Many natural check-dams, such as the Balihe Gully and Sanshilihe Gully in the Shannxi Province, the Laobatou and Qianqiuzi in the Gansu Province, and so on, all have achieved relative stabilization. The Huangtuwa in Zizhou County of Shannxi Province, another famous natural check-dam covering 40 ha^2 of lowlands, has favorably run for more than 400 years. Some check-dam systems built in the 1960's, such as the Kanghe Gou dam system in Shanxi Province and the Wangmao Gou dam system in Shannxi province, are also typical projects attaining relative stability, and have retained enormous sediments and harvested plentiful crops.

Equipmental Procedure

The model experiment was designed according to the data on soil and water of Yangdaogou Gully, one of the typical small watersheds in the Loess Hill Ravine Region of Loess Plateau. Instead of simulated rainfall, runoff in the gully was applied to simulate the movement of soil and water in these experiments since gully erosion is high correlated between the flowrate. Although impact of raindrops affects soil and water loss caused by very thin sheet flow, it makes almost no influence on that by rill or gully flow for water layer cushions the impact of the rainfall (Huang *et al.*, 1996; Schultz *et al.*, 1985). Ghadiri and Payne (1981) and Mutchler and Larson (1971) showed that the peak soil splash weight occurred when the depth of pounding was between 0.14 and 0.20 of the drop diameter and decreased toward zero as the depth of pounding approached three drop diameters. Schultz *et al.* (1985) illustrated that about three millimeters of water pounded on the soil surface or 1.88 times the raindrop diameter effectively stopped the soil splash from the container for the 1.66 mm raindrop size. Rill erosion and gully erosion are the main types in the Loess Plateau, which account for 60-90% of the total (Zhang, 1993). Result of field tests on erosion of small watershed indicated that the runoff contribution to soil erosion could be developed a power regression equation (Cai *et al.*, 1998). Thus appropriate runoff could simulate the process of soil and water loss in gullies.

Experiments were carried out at the Laboratory Hall of Yellow River Research Center, Tsinghua University, Beijing, PR China. According to demand of the experiment and condition of the laboratory, we confirmed the length scale λ_z as 60. Essential predigestion on the microrelief of this area was made without deforming the characteristics of soil and water loss in the prototype area in order to demonstrate the commonness of the small watershed in the Loess Plateau. The soil was the matrix loess collected from Shunyi district, Beijing, and was passed through the 1cm sieve pore to remove large clods, debris and grass roots, which is constituted as table 1. The 50% diameter of soil particle D_{50} is 21.4 μm, and the dry density γ_o is 1.436 x 10^3 kg m^{-3}. To ensure a regular original microrelief, the soil was patted by hand to generate a smooth roughness. According the similarity law on hyperconcentrated flow (Zhang *et al.*, 1993), model scales for the experiment are described as table 2.

The experimental system was made up of the water circuit and the gully model, as illustrated in Figure 1. Water and loess were added into the round puddling pool and whisked by the spin puddler to be well-proportioned enough, then the mixture was pumped to the constant head tank. To prevent the sediment from subsiding, a reciprocating puddler was set up in the constant head tank. As the sediment-laden fluid flowed into the gully model, part of it was restored in the upstream of the check-dam and the other arrived at the storing pool. To prevent the runoff from changing the sediment concentration in the puddling pool, a valve was set at the end of the storing pool. However, when one sequence of experiment was completed, the valve could be opened, and then fluid in the storing pool could be released into the puddling pool, which could be reused in the next experiment. The gully model covered an area of 14 m by 3.5 m. The section of the branch gully at the foreside of the model was "V" shaped and the section of the main gully at the rearward was "U" shaped. The length of the branch gully was about 9 m. The dam-site was at the main gully was 0.9m from the end of the branch, which standed for the entrance of the prototype main gully. In the Loess Plateau, the middle-scale check-dams, from 15-20 m high, are almost located in the entrance of the main gully (Jiao, 2002). The effective height of the dam was 0.35 m before runoff. A spillway is located in the left side of the check-dam, which allows the floodwater to overflow into the storing pool.

Among the inlet pipes, an electric flowmeter was fixed to measure the flux invading the gully. The two sidewalls, which were straddled by a measurement bridge with a height finder, were parallel and their tops were correspondingly in the same altitude. The bridge could ride along the sidewalls and the height finder could slide along the bridge, thus the elevation of any point on the gully bed could be measured. Eighteen experiments were conducted with the same flux 1 x 10^{-3} m^3 s^{-1} and the same duration 12 minutes. The sediment concentration of the flow to the gully was kept to approximate 80-100 kg m^{-3}. A 24-h break was followed after every runoff. The initial microtopography made according to the blueprint of scale model was identified as “I(0)”, and that after the first runoff was identified as “I(1)”, and that after the second runoff was identified as “I(2)”, etc. Every microrelief 24 hours after runoff was the initial landform of the next sequence. Before the next runoff, muddy water stored in the reservoir in front of the check-dam was defecated and pumped out, and the microrelief of the gully bed should be measured by the height finder. For this study, surface elevation was digitized for both horizontal directions in 0.1 m grids.

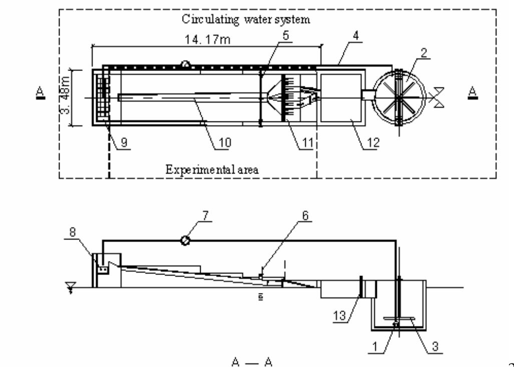

Figure 1. The fro **gully with a check-dam**

1. Submersible centrifugal pump; 2. Puddling pool; 3. Spin puddler; 4. Inlet pipe; 5. Measurement bridge; 6. Height finder; 7. Flowmeter; 8. Reciprocating puddler; 9. Constant head tank; 10. Gully; 11. Check-dam; 12. Storing pool; 13. Valve

Referring to ASL (Casalý *et al.*, 1999), we define SL as the length-weighted average slope gradient:

$$SL = \frac{\sum L_i S_i}{\sum L_i} \qquad (1)$$

where L_i is the length of every segment of the gully, S_i is the slope gradient of this segment with uniform characteristics. In these experiments, L_i and S_i could be calculated based on the coordinates along the gully thalweg. Table 3 is a sample to calculate SL, where x is the distance to the check-dam, and z is the elevation. The calculated SL of every sequence is shown as Figure 6. An important index of relative stability is that the annual sedimentation thickness in the late age of forming dam-land is so little that the workload for heightening the dam could be afforded by the local people (Zeng *et al.*, 1999). In order to measure the mean elevation of dam-land after every runoff, we had drawn the dam-land contour of every sequence with the software Surfer 7.0. An example is shown in Figure 2. Where the area closed with dashed line, is the dam-land, and its elevation is 1.05 m. Variation of the dam-land elevation after every runoff is illustrated in the Figure 7. The increment of alluvium area is a concernful reason to maintain check-dams relatively stable. Based on the contour graph drawn by Surfer 7.0, a *.dxf file was created and then imported to the AutoCAD 2000. According the feature of the landform, it’s easy to outline the borderline of alluvium, as the area closed by the dashed line in the Figure 3. Then with the command “area”, we could gain the area of the alluvium. Variation of the alluvium area after every runoff is illustrated in the Figure 8.

Results and Discussion

Possibility and threshold of the relative stability

The initial sections of the gully before any runoff are symmetrical, and the point in the symmetrical axis is the lowest, as illustrated in plate 1. All elevations of these points had been observed once every 0.1m after every runoff. Figure 4 shows some groups of the observed data. In Figure 4, the thalweg could be definitely divided into two parts: the area in the range of 2.5 m in front of the check dam is influenced by the dam and is the alluvial area, and the other is the erodible area. In the former area, the later sequence is, the less silt thickness is caused by every runoff. However, in the later area, except I(1) to I(3), the scoring thickness of every sequence is very little. That’s to say, as the time go on, the gully with a check dam is becoming more and more stable. According the rising trend of the gully bed, the sedimentation thickness of the I(1) should be larger than that in the I(2). However, in Figure 4, the variogram is different, because the original landform showed in this figure was made according to the blue print and the water content of the soil is not saturated. After the I(1) runoff , the heights of the gully bed will decline due to the smaller spacing rate. In fact, the increment of the gully bed is larger than that in the Figure 4.

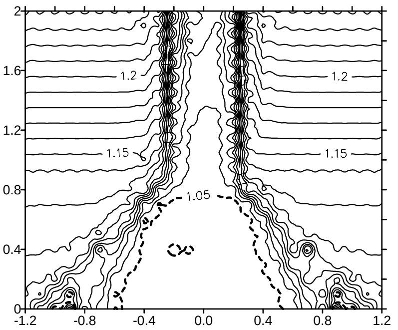

Figure 2. Landform of the dam-land (I(17))

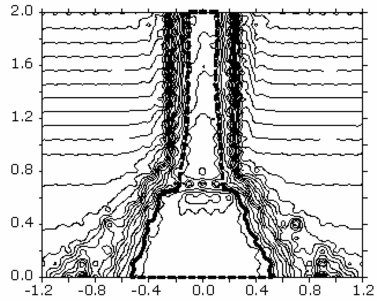

Figure 3. A sample to measure the area of alluvium

Although all of the elevations of the dam land after every runoff show increasing trend (Figure 5), the slope is steep before the I(12), and is very gentle after I(12). That means, after I(12), the mean elevation of the dam-land is almost constant, the check dam need not be heightened any more during the I(12) to I(17). The ultimate elevation of dam-land in this experiment is about 1.05m. In this paper, the ultimate elevation of dam-land keeping constant is defined as the critical dam-land elevation.

The SL vs. Sequence relationship in Figure 6 shows a degressive trend, with a steep slope before the I(8), and a gentle gradient after I(8). However, after I(13), they have almost become a horizontal trend. That means, the gully has become relatively stable, and the slope varies a little, despite of puny variations in microtopography. The minimum SL of the gully with a check-dam after sequences of floodwater is called the critical mean slope gradient of the gully. In this group of experiments, from the I(13) sequence on, the gully with a check dam has become relatively stable and the critical mean slope gradient is 7%, and the corresponding threshold mean angle is 4°.

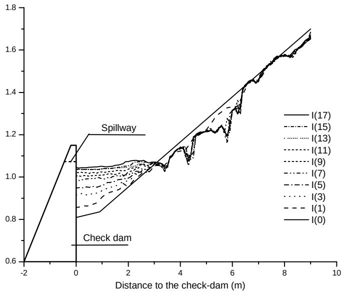

Figure 4. Variation of the thalweg after every runoff

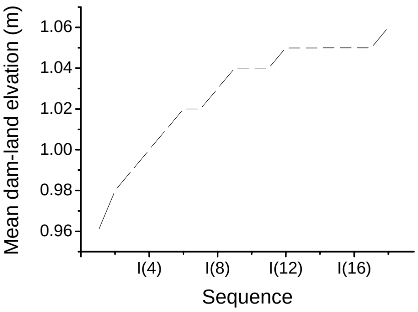

Figure 5. Variation of the mean dam-land elevation after every runoff

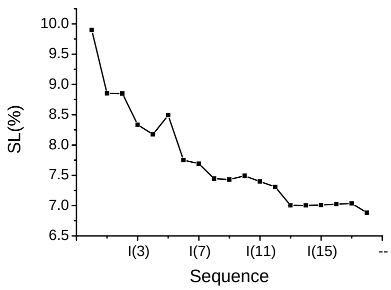

Figure 6. Mean slopes after every runoff

Mechanism for the relative stability

Just like any other water-blocking structure, such as reservoir, retention pond, etc., the check dam slows down the velocity of the sediment-laden water, which results in lower sediment transport capacity. Thus some of the sediments sink and the sediment concentration in the outlet is smaller than that in the inlet. Moreover, before the next runoff, the sediment-laden fluid stored above the dam-land becomes clear and leaves sediment on the dam-land to prevent the dam-land from erosion. On the other hand, the development of a "shield" layer composed of relatively heavy soil particles protected the underlying soil from runoff erosion. When the soil surface was initially inundated with runoff, soil particles were detached from the soil surface and entrained into the gully flow. Light particles, with low settling velocities, would move far from their original location, but heavy particles will settle quickly near their original positions. If this process continued, eventually most of the lighter particles would be removed, leaving a shield of heavier particles that protected the underlying soil. Figure 7 shows the variation in size composition of sediment in surface of the gully bed after 18 runoffs.

As the dam-land went up, its area expanded subsequently in virtue of the sloping gully bank. Figure 8 illustrates a linear rising trend of the dam-land area. Consequently even if the bulk of the intercepted sediment were the same, the dam-land would less go up thanks to augment of the area after every runoff. However, other elements bring on check-dam relative stability too. For examples, as the dam-land rose, the reservoir capacity decreased and less sediment-laden fluid could be stored in the upstream of the check dam. As a result, the amount of deposited sediment decreased too. In fact, In the anaphase of integrative control on the small watershed of Chinese Loess

Plateau, the dam-land increases more slowly owing to the great reduction of the amount of sediment originated from the slopes and gullies, which causes less flood magnitude and smaller sediment concentration.

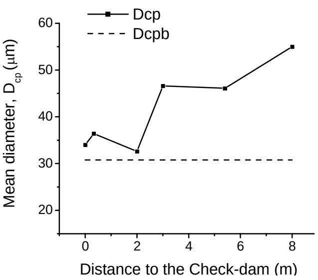

Figure 7. Coarsening of the gully bed after runoffs

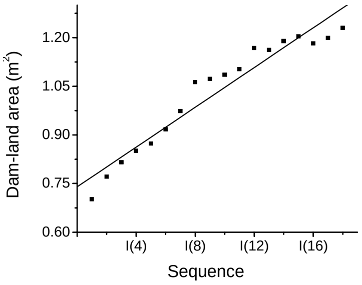

Figure 8. Variation of the alluvium areas after every runoff

Summary and Conclusions

A laboratory study of gully flow was conducted to demonstrate the condition and mechanism for relative stability of check-dams in Loess Plateau, China. This study developed sequence dependent relationships between mean slope gradient, mean dam-land elevation, and the dam-land area. When more and more sediment leaves behind on the dam-land, the dam-land area grows subsequently and becomes so large that the mean dam-land elevation and mean slope gradient keep almost constant. As a result, the check-dam needs not be heightened or the workload for heightening the dam could be afforded by the local people. The ultimate elevation of dam-land keeping constant is defined as the critical dam-land elevation. The minimum SL of the gully with a check-dam after sequences of floodwater is called the critical mean slope gradient of the gully. From the I(13) sequence on in this experiment, the gully with a check dam had become relatively stable and the critical dam-land elevation was 1.05m, the critical mean slope gradient was 7%, and the corresponding threshold mean angle was 4°. It is an effective and rapid way to calculate the mean dam-land areas and the mean dam-land elevations by drawing gully-bed contour of every sequence with the software Surfer 7.0. This paper presents a recapitulative method to design a model experiment in the laboratory to test the relative stability of the check-dam. However it is more difficult to design a scale model experiment on quantitative erosion in a designated area. Despite it is more economical, repeatable, and quick to study soil conservation by model scale experiment in the laboratory than to research in field, few researches on similarity for the former have been conducted due to the complicated mechanism of soil and water loss. More research into the corresponding theories and experiments to predict the soil and water loss and to optimize the layout of check-dam system in a small watershed by scale model experiments is needed.

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References

Casalý, J., Lopez, J.J., Giraldez, J.V. (1999). Ephemeral gully erosion in southern Navarra Spain, *Catena* 36, 65–84

Cai, Q.G., Wang, G.P., Cheng, Y.Z. (1998). The process and simulation of soil erosion for small watersheds in the Loess Plateau, China, *Science Press*, 135-137(in Chinese)

Fang, X.M. (1995). Criterion and condition for the relative stability of check-dam system, *Soil and Water Conservation in China*, no.169: 29-33(in Chinese)

Fang, X.M., Wang, Z.H., Kuang, S.F. (1998). Mechanism and Effect of Check-dam to Intersect Sediment in the Middle Reach of Yellow River, *Journal of Hydraulic Engineering* 20, 49-53 (in Chinese)

Foster, G. R. (1982). Modeling the erosion process, in: Hydrologic Modeling of Small Watersheds, C. T. Hann, H. P. Johnson, and D. L. Brakensiek (eds.), *ASAE Monograph*, St. Joseph, MI, 297-380

Gardiri, H. and Payne D. (1981). Raindrop impact stress, *J. Soil Sci*. 32, 41-49

Huang, C.H., Bradford, J.M., and Laflen, J.M. (1996). Evaluation of the detachment — Transport Coupling Concept in the WEPP Rill Erosion Equation, *Soil Science Society of America Journal* 60, 734-739

Jeff, W., Melanie, D., Duncan, W. (2002). Stability of an upland gravel-bed stream, Swinhope Burn, Northern England, Catena 49: 309-329.

Jiao, J.R.(Chief in editor) (2002). Collection of the criterion on hydraulic technology: Technical criterion on comprehensive control of soil and water conservation in gullies, Chinese Hydraulics and Hydropower Press, 215-229 (in Chinese)

Lei, Y.J., Zhu, X.Y. (2002). Formation, Control Principle and Method for Relative Stability of Check-dam System, Yellow River, no.2: 23-26.

McEwen, L.J. (1994). Channel planform adjustment and stream power variations on the middle River Coe, Western Grampian Highlands, Scotland, *Catena*, 21: 357– 374

Mutchler, C.K. and Larson, C.L. (1971). Splash amounts from waterdrop impact on a smooth surface, *Water Resources Research*, 7, 195-200

Novak, M.D. (1985). Soil loss and time to equilibrium for rill and channel erosion, *Trans. ASAE*, 28(6): 1790-1793

Schultz, J.P. Jarrett, A.R, Hoover, J.R. (1985). Detachment and splash of a cohesive by rainfall, *Trans ASAE*, 28(6): 1878-1884

Sidorchuk, A. (1999). Dynamic and static models of gully erosion, *Catena* 37, 401–414

Warburton, J., Davies, T.R.H., Mandl, M.G. (1993). A meso-scale field investigation of channel change and floodplain characteristics in an upland braided gravel-bed river, New Zealand. In: Best, J.L., Bristow, C.S. (Eds.), Braided Rivers. Geological Society Special Publication, vol. 75. The Geological Society, London, 241–255

Xu, X.Z., Zhang, H.W., Zhang, O.Y. (2004). Development of Check-Dam Systems in Gullies on the Loess Plateau, China, *Environmental Science and Policy* 7, 79-86.

Zeng, M.L., Fang, X.M., Kang, L.L., Wang, E.P. (1995). It is Doubtless for the Check System in Gullies to Become Relativly Stable, *Yellow River* 17: 18-21

Zeng, M.L., Zhu, X.Y., Kang, L.L., Zuo, Z.G. (1999). Effect to Intercept Sediment and Decrease Erosion and development prospect of Check-dams in Water and Soil Erosion Areas, *Research of Soil and Water Conservation* 6, 127-132 (in Chinese)

Zhang, H.W., Jiang, E.H., Bai, Y.M. (1994). Similarity law for physical model of the hyperconcentrated flow in Yellow, *Henan Science & Technology Press* 80, 115, 156~162 (in Chinese)

Zhang, T.Z.. (1993). Discussion Outline on Loess Plateau, Environment Press of China, 109 (in Chinese)

Table 1. Distribution of the sediment diameters before runoff

Particle diameters (μm)	≤ 5	≤ 10	≤ 15	≤ 25	≤ 50	≤ 75	≤ 100
Cumulative weight (%)	17.375	25.575	34.575	53.25	78.925	92.575	100

Table 2. Model scales for the experiment

Scale	**Value**	**Narration**
Length	$\lambda_L = 60$	Restricted by the experimental ground
Velocity	$\lambda_v = \lambda_L^{1/2} = 7.75$	Similarity for gravity
Flowrate	$\lambda_Q = \lambda_L^{5/2} = 27885$	$\lambda_Q = \lambda_L \lambda_h \lambda_v$
Rough rate	$\lambda_n = \lambda_R^{2/3} / \lambda_L^{1/2} = 1.98$	Similarity for resistance
Time	$\lambda_t = \lambda_L^{1/2}$	$\lambda_t = \lambda_L / \lambda_v$
Dry bulk density	$\lambda_{\gamma_0} = 1$	Loess analogical to the prototype is applied as the model sediment;
Sediment concentration	$\lambda_s = 2$	Similarity for the sediment transport capacity; $\lambda_s = 1.15 \sim 3$

Table 3. A sample for calculating the average gradient of the gully thalweg

No.	Coordinate(m) x	Coordinate(m) Z	Gradient	Angle(°)	Length(m)	AL(°)	SL
1	0	1.05				3.936184	0.078133
2	0.1	1.048	-0.0200	-1.14576	0.10002		
3	0.2	1.048	0.0000	0	0.1		
•	•	•	•	•	•		
90	8.9	1.649	0.1200	6.842773	0.100717		
91	9	1.651	0.0200	1.145763	0.10002		

Notes: 1. $Slope_i = \dfrac{z_{i+1} - z_i}{x_{i+1} - x_i}$; 2. $Angle_i = A\tan(\dfrac{z_{i+1} - z_i}{x_{i+1} - x_i})$;

3. $Length_i = \sqrt{(z_{i+1} - z_i)^2 - (x_{i+1} - x_i)^2}$;

4. $AL_i = \dfrac{Angle_i * Length_i}{Length_i}$; 5. $SL_i = \dfrac{Slope_i * Length_i}{Length_i}$