Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

ISSN: 0972-6268 | Vol. 14 | No. 2 | pp. 267-274 | 2015

Original Research Paper

The Study of Terraced Field Erosion Based on the Scale Model in the Loess Plateau under Extreme Rainstorm Conditions

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com
Received: 24-8-2014
Accepted: 30-9-2014

Key Words:
Loess plateau
Terraced field
Artificial rainfall experiment
Extreme rainstorm
Erosion

ABSTRACT

The terraced field was an important way to develop the high-efficiency agriculture on the loess plateau, however, lots of terraced field were heavily damaged by the extreme rainstorm in 2013. Improving the terraced field design standard had become a difficulty in recent research. Based on the field observation and similarity theory, this paper constructed a 1:10 terraced field scale model. The artificial rainfall together with water releasing experiments were designed to simulate the soil erosion process in the scale model. The experimental results revealed that the erosion process of the prototype in extreme rainstorm could be reappeared under the experimental condition that the rainfall intensity was 0.395 mm/min and the experiment lasting time was 2.68 hours. Both the erosion amount and the erosion gully topography of the scale model could be verified by the measured data of the prototype. It can be inferred that the equivalent erosive precipitation of the extreme rainstorm was 636 mm. And it was an effective method to research the soil and water erosion process and the terraced field design standard utilizing the terraced field scale model.

INTRODUCTION

As one of the most important soil and water conservation measures, the terraced field was widely distributed in the loess plateau where serious soil and water loss happens. Its area had reached to 6050000 hectares in the early 20th century (Tang 2004). The previous studies have shown that the soil and water conservation efficiency of the terraced field could reach up to 95%-100%, playing an important role in the sloping field governance in the loess plateau (Jie et al. 1986, Jiao & Wang 1999, Yao & Wang 1992). Lots of measured data indicated that the terraced field could almost retained the individual rainfall less than 200 mm, with no runoff flow out (Ran et al. 2006). Most of the monthly rainfall was less than 100 mm in this area, except July and August. And most of the monthly rainfall in July and August was more than 100 mm but less than 200 mm, rarely more than 200 mm (Jie et al. 2002). In this situation, the terraced field could completely retained all of the rainfall, producing no water and soil loss. Even if the runoff could overflow the ridge when the rainfall was large enough, the terrace ridge would turned into a multistage hydraulic drop to consume the flow energy (Ran et al. 2006). Researchers (Jie et al. 1986) proved that reducing the slope gradient could decrease the runoff coefficient, and shortening the slope length was one of the three important measures to improve soil erosion conservation in theory.

Most of the rainfall did not produce runoff in the loess plateau. Only several heavily rainstorms could cause severe soil erosion (Zhou & Wang 1992, Pute & Gao 2006). Luo (1964) explained the reasons why the terraced field could be destroyed in detail according to the investigation in the west of Shan'xi province from 1962 to 1963. The bench terraces, one of the most widely used type of terraces in the loess plateau, had a good effect in holding most of the rainfall. But it could be destroyed at the terrace ridge by extreme rainstorm, causing serious gully erosion.

Lots of buildings and terraced field were destroyed by the 2013 extreme rainstorm in Yan'an. According to the rainfall data published by Water Conservancy Bureau of Shaanxi, the total precipitation had climbed to 1000.9 mm in this area from June to September. And the erosive precipitation was 886 mm. In order to research the terraced field erosion rules in the extreme rainstorm events, this paper constructed a 1:10 terraced field scale model based on the similarity scale relationship (Gao et al. 2005, Gao et al. 2006) and field observation in MaJiaGou watershed. Artificial rainfall together with water releasing experiments were designed in the terraced field scale model, to simulate the erosion and destruction process of the prototype.

MATERIALS AND METHODS

Overview of the watershed: The prototype of the terraced

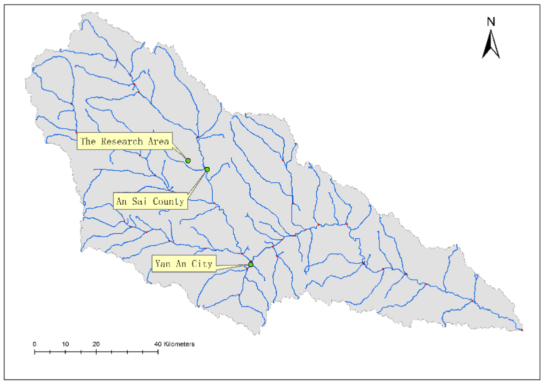

Fig.1: Location of the research area.

field was located in the MaJiaGou watershed, belonging to the hilly-gullies region of the loess plateau, as shown in Fig. 1. The soil erosion module was more than 12000 t/(sq. km*a) in this area. The terraced field was consisted of 8 bench terraces, and the catchment area was about 25014 sq. m.

Full station measurement has been taken 4 times since 2013/4/9, as shown in Fig. 2. The terraced field was firstly destroyed slightly, and then be repaired by filling soil into the erosion gully in May. The depth of the erosion gully was about 3 m, the length was about 17 m, and the breath was about 10 m.

The extreme rainstorm analysis: The extreme rainstorm lasted from June to September. The daily precipitation of AnSai station is listed in Fig. 3 from 2013/6/1-2013/9/30, and the total precipitation was 1000.9 mm. Based on the 59 years statistic data of Yan'an station, this rainfall frequency was less than 0.01.

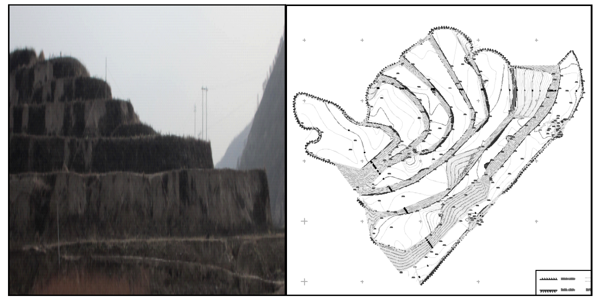

Fig. 2: The picture of the terraced field and measured topographic map.

The similarity scale of the terraced field model: This experiment using the hydrology erosion model similarity scale raised by Gao Jian'en (Gao et al. 2005, Gao et al. 2006). The geometric scale used in this experiment was selected as 10. And the primary similarity scale expression are listed in Table 1.

The model sediments: The median diameter of the prototype terraced field was 0.028 mm. According to the suspended load similarity, the suspended load scale $\lambda d = 1.78$. And the median diameter of the model sediments was 0.028/ 1.78 = 0.157 mm. The soil grain composition curve showed that the soil sample in Dongbo village of Yangling could meet the suspended load similarity requirement (Fig. 4).

According to the sediment-moving incipient velocity curve raised by Hazen (Fig. 5), the sediment-moving incipient velocity of the prototype was 0.09 cm/s (the median diameter of the prototype was 0.028 mm), the sediment-

Table 1: The primary similarity scale of the terraced field model.

Name		Symbol of the scale	The scale value
Geometric scale	Horizon scale	λ_l	10
	Vertical scale	λ_h	10
Rainfall scale	Raininess scale	$\lambda_i=\lambda_V=\lambda_l^{1/2}$	3.16
	Precipitation scale	$\lambda_p=\lambda_l\,\lambda_i$	10
	Rainfall time scale	λ_{t1}	3.16
Hydraulic scale	Flow velocity scale	$\lambda_V=\lambda_l^{1/2}$	3.16
	Flow quantity scale	$\lambda_Q=\lambda_l^{2/5}$	316.23
	Roughness scale	$\lambda_n=\lambda_l^{1/6}$	1.47
	Flow time scale	$\lambda_{tl}=\lambda_l^{1/2}$	3.16
Erosion sediments scale	Suspended load scale	$\lambda_d=\frac{\lambda_l^{1/4}\lambda_v^{1/2}}{\lambda^{1/2}_{\frac{\rho_s-\rho}{\rho}}}$	1.78
	Start simulation	$\lambda_V=\lambda_l^{1/2}$	3.16
	Sediment concentration scale	λ_s	3
	Deformation time scale	λ_i	3.3
	Sediment discharge scale	λ_G	300000
Soil water scale	Soil moisture content scale	λ_e	1
	Infiltration rate scale	$\lambda_f=\lambda_V=\lambda_l^{1/2}$	3.16

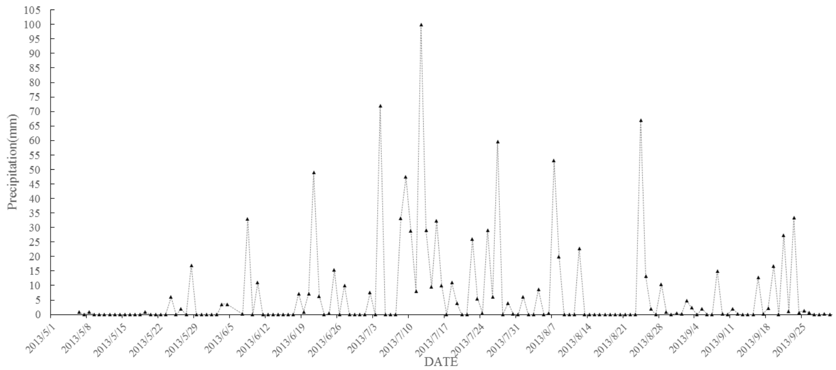

Fig. 3: The daily precipitation from 2013/5/1-2013/9/30.

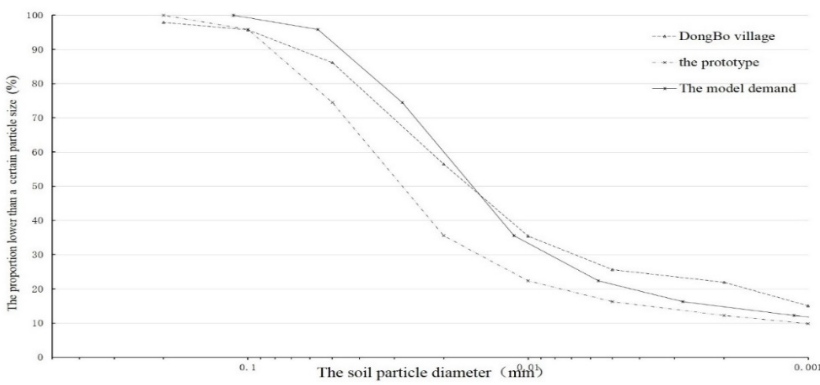

Fig. 4: The soil particle diameter curve.

moving incipient velocity of Dongbo village was 0.028 cm/s (the soil median diameter was 0.015 mm).

$\lambda u_c = 0.09/0.028=3.21$

In this situation, it could meet the sediment-moving incipient similarity requirement approximately.

The design of the experiments: In the north and middle of the loess plateau, the erosive precipitation can reach to 140-150 mm, and the average erosion frequency was 5-7 times yearly. On the condition that the total precipitation was unchanged, it was assumed that there was a constant rainfall process which, destroyed the terraced field. Artificial rainfall together with water releasing experiment was used to seek for the rainfall process in the terraced field scale model. According to the field measures of the prototype, the experimental results were verified. When the experimental results were verified, the rainfall process was considered as the equivalent rainfall process, and the runoff and sediments motion rules could be used in the prototype.

According to the relationship graphic of the rainfall intensity, recurrence interval and rainfall lasting time, the rainfall intensity and lasting time could be referred in the graphic (Fig. 6). And the extreme rainstorms had appeared on the loess plateau are listed in Table 3. Eight groups of the experiments were designed as follows (Table 4).

Preparation of the experiment: The experiment was conducted in the rainfall hall of the institution of soil and water conservation of CAS & WMR. The artificial rainfall system was the down spray rainfall system. The efficient rain-

Table 2: The rainfall intensity and lasting time in the 10000 years rainstorm standard.

Rainfall lasting time (min)	Rainfall intensity (mm/min)
10	3.3
30	2.27
60	1.36
120	1.15

Table 3: The extreme rainstorm on the loess plateau.

Rainfall lasting time (min)	Precipitations (mm)
26	107.3
60	252.8
120	223

Table 4: The design of the experiments.

Experiment groups	The prototype rainfall intensity (mm/min)	The model rainfall intensity (mm/min)	The prototype rainfall lasting time (h)	The model rainfall lasting time (h)	The prototype flow volume (m^3/s)	The prototype flow volume (L/s)
1	0.8	0.25	20.8	6.58	0.2	0.63
2	1.25	0.4	13.33	4.2	0.31	0.99
3	1.36	0.43	12.25	3.88	0.34	1.08
4	1.86	0.59	8.97	2.84	0.46	1.47
5	2.27	0.72	7.35	2.33	0.57	1.79
6	3.3	1.04	5.05	1.6	0.83	2.61
7	4.21	1.33	3.96	1.25	1.05	3.34
8	5.91	1.87	2.82	0.89	1.48	4.68

Table 5: The experiment conditions and erosion volume.

Experiment groups	Rainfall lasting time (min)	The model erosion volume (m^3)	Switched to the prototype erosion volume (m^3)
1	181	0.263	263
2	161	0.261	261
6	76	0.263	263
7	25	0.259	259
8	25	0.261	261

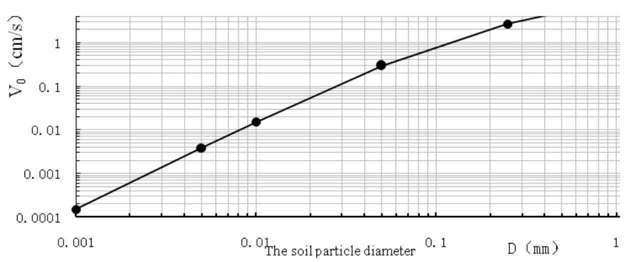

Fig. 5: The sediment-moving incipient velocity curve.

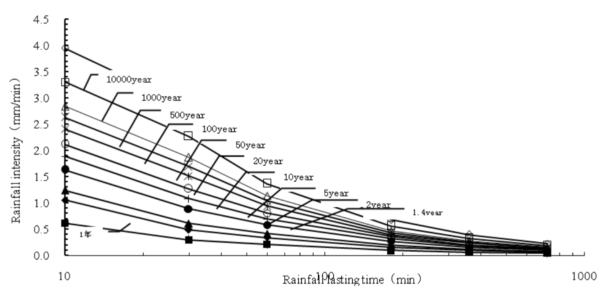

Fig. 6: The relationship of the rainfall intensity, recurrence interval and rainfall lasting time.

fall area was 16.25m×24m, and the height of the rainfall system could reached to 16m. The rainfall intensity of the system was ranged from 15~250 mm/h, and the rainfall uniformity was higher than 75%. A 1.5 m × 2 m × 0.6 m steel soil bin was used in the experiment. In the soil bin, 50 cm depth soil were filled by 10 layers, to guarantee the soil unit weight was set as 1.3 g/cm^3 from the bottom to the top. The soil used in the experiment was collected from Dongbo village of Yangling. All of the soil was sieved by 1 cm × 1 cm mesh screen before filled into the soil bin, in order to wipe off the gravel and grass roots etc. At the beginning of each experiment, water was purled on the surface soil slightly to keep the surface soil moist and reached saturation moisture content. That could lower or even remove the influence of the initial moisture content to the soil erosion. The water was firstly pumped to a water tanker, which was set at the upward side of the soil bin, to ensure that the water could flow steady to the soil surface (Fig. 7).

After the rainfall intensity and the flow was calibrated well, the waterproof covers on the soil bin were opened, and then the rainfall system was turned on and the rainfall lasting time was recorded at the same time. After the terraced field model started producing the runoff, silt carrying flow was collected utilizing the labelled plastic drum every 10 minutes. And during the process of the experiment, the terraced model topography was measured every 20-30 minutes at several typical cross sections using the steel rules. The sediment concentration of each sample was measured by oven drying method.

RESULTS AND DISCUSSION

Flow velocity: Terraces scale model velocity changing with time is shown in the Fig. 8. As can be seen from the velocity change process, the flow velocity increased rapidly early and fluctuated later under the combined effect of rainfall and flow. The above results were more consistent with previous research (Liu et al. 2011, Catherine et al. 2010, Wang et al. 2014) on rill erosion.

The experiment results revealed that the average flow velocity was raised as the rainfall intensity and flow raised. That was consistent with the previous research that the velocity increased with the increasing of runoff in the artificial rainfall situation (Liu et al. 2011).

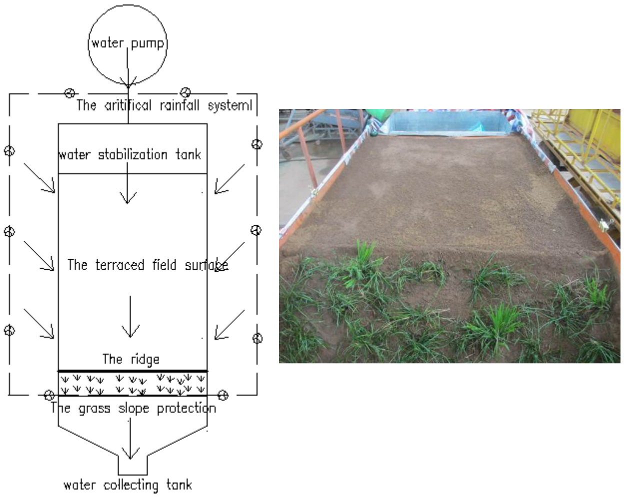

Fig. 7: The experimental plan.

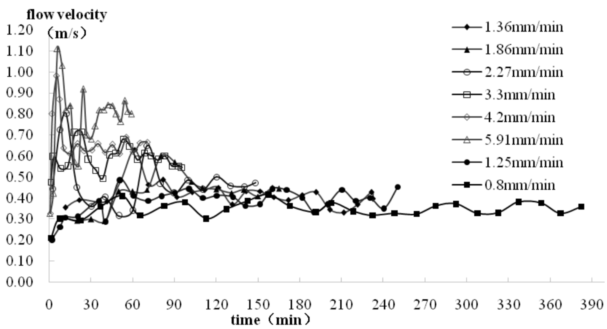

Fig. 8: The velocity change curves.

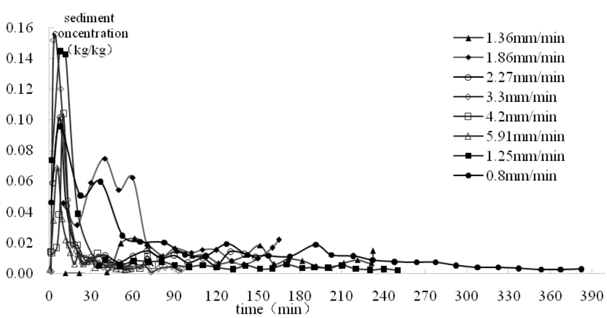

Fig. 9: The sediment contraction change curves.

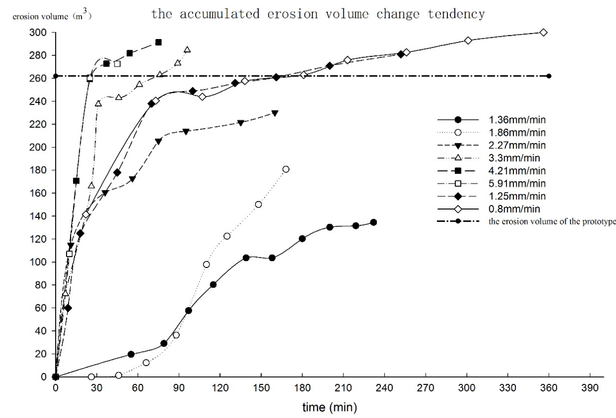

Fig. 10: The accumulated erosion volume change tendency.

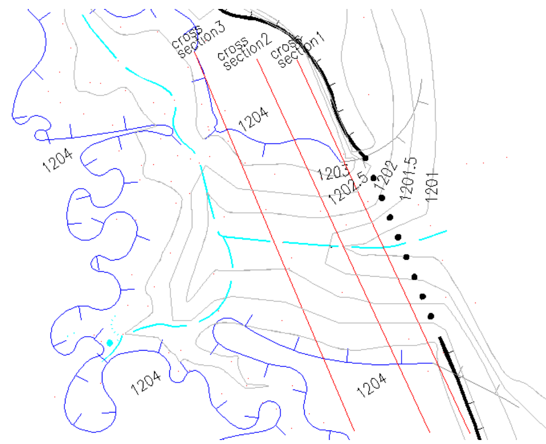

Fig. 11: The three typical cross sections plans in the erosion topographic map.

Through the velocity changing curve, it could be inferred that all the groups of the experiment velocity rising rapidly at the beginning, and then declining gradually and fluctuating stably at the end. Previous research has found that the flow velocity change trend has a significant relationship to do with rill morphology in the rill erosion. And similarly, the terraces model velocity variation was the response of the terrace erosion process. At the beginning of the experiment, the overland flow was gradually formed. The surface flow type changed from slowly to urgently, and the velocity curve increased gradually along with rainfall duration. After the ridge was destroyed, water flowed out of the field surface quickly. The velocity increased instantaneously, and the curve raised rapidly. The velocity variation was consistent with rill erosion process. Previous research suggested that velocity would decrease as the water flowed into the drop in the rill erosion. On the contrary, velocity would increase after water flowed out the drop (Liu et al. 2011, Wang et al. 2014).

Raindrops and surface flow has limited effect on the sediments detachment and motions before the ridge was destroyed. As ridge was washed out, drop was formed at the ridge, which caused the field surface slope changing. The sediment detachment and carrying capacity of the flow was greatly changed. And then the water flow exacerbated erosion on the field surface. Slope surface erosion processes

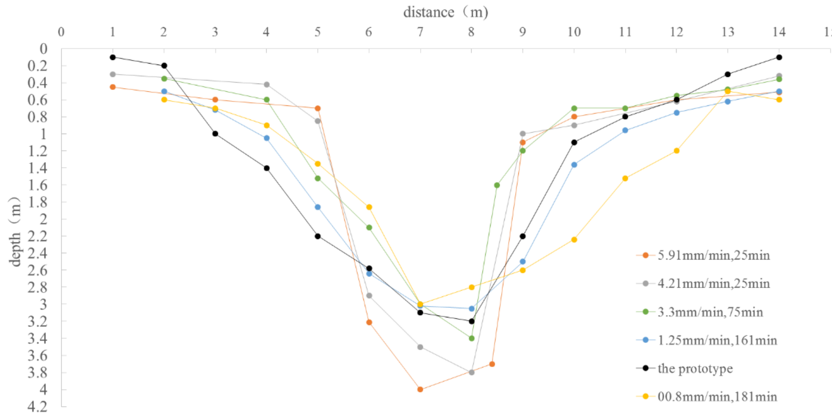

Fig. 12: The first cross section comparison.

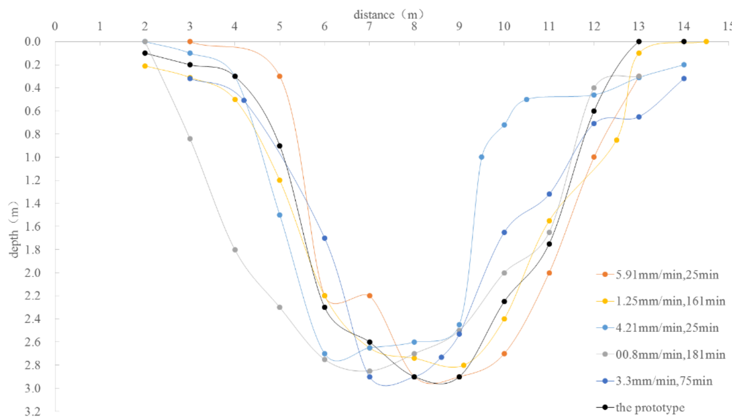

Fig. 13: The second cross section comparison.

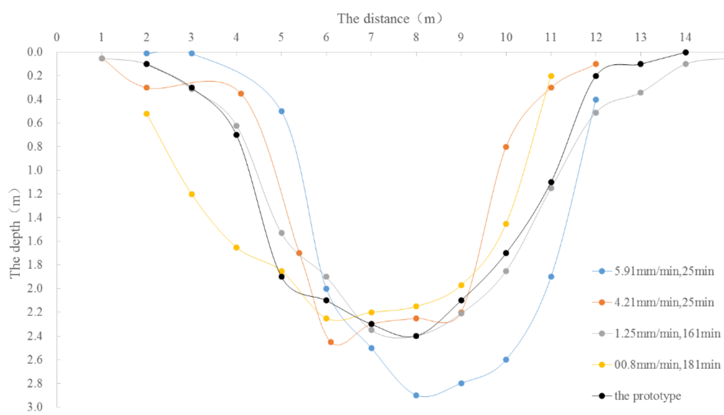

Fig. 14: The third cross section comparison.

developed with it gradually. Soil erosion transited from rill to shallow ridges and gully. Flow kinetic energy was consumed constantly in the process of the soil erosion and sediment transportation. At the same time, water drop in the ridge also consumed the flow kinetic energy constantly. Flow velocity reduced further and then fluctuated constantly, when erosion gully down-cutting and lateral erosion cutting process gradually become stabilize.

After the destruction of ridge, the nature of terrace erosion process was headward erosion caused by the erosion base level declining. The erosion base level declining gradually increased the slope of underlying surface, which would transform the water potential energy into kinetic energy, and the sediment carrying capacity was reinforced. Erosion occurred in the new outcropping of the river, and then gradually developed to the upstream repeatedly, and finally formed the headward erosion.

Sediments concentration: The sediment yield change tendency is shown in Fig. 9. At the beginning of the experiment the flow velocity was low. The flow has limited effect on striping and transporting the surface sediments. And the sediment concentration was almost zero, which was also the embodiment of the terraced field benefits on soil and water conservation. In the case that the ridge kept intact, the effect of terraced field on soil and water conservation was obvious and the surface erosion could be ignored.

After the ridge was destroyed, water gradient changed rapidly, which increased the flow velocity quickly. The drop was firstly formed, and then a rill erosion came up. The length and width of the rill raised gradually. Rill turned into shallow gully, cutting groove furrow in further development, and then caused the traceability erosion. At the same time, the water potential energy was switched into kinetic energy. That greatly improved its soil erosion ability on the surface sediments, which caused a severe soil erosion in a short time near the terrace ridge. The depth of erosion gully increased rapidly as the water incising effect getting enhanced, and gully shape presented as a V-shaped at this time. The sediment concentration raised rapidly to the maximum value as the development of rill, shallow groove, gully and the collapse of terraced ridge and slope protection.

After the erosion gully incised to a certain degree, the erosion gully width increased gradually and formed a U-shape with the constantly lateral process. When undercutting and lateral turned to be stability, the shape of the erosion gully achieved basically stability period and the erosion process gradually weakened and became stabilized. The sediments contraction curve gradually declined after rapid climb, and fluctuated steadily at the end. Relevant research results had indicated that the headward erosion was the most active sediment yield factor in the development of rill. It provided most of the grains of sand, nearly more than 50% of total rill erosion in the early period of the rill erosion. Sediment yield caused by collapse of the trench wall was relatively low. Headward erosion was mainly caused by the scouring and down-cutting of gully head runoff, but the collapse of trench wall was mainly affected by gravity, which had a close connection with the slope (Han et al. 2002).

Previous studies on the slope rill erosion process had found that slope sediments, changing trend in the process of rainfall roughly, could be divided into the three periods (Wang et al. 2014, Han et al. 2002), decreasing firstly (period I), then gradually rising (period II), and gradually reducing and stabilizing lastly (period III). The experiment results (Wang 2002) showed that the slope sediment increased rapidly and fluctuated steadily at 0.1 (g/mL). Terraces model sediment contraction change process was consistent with that.

The verification of the model: According to the field measurement on the prototype, using the ArcGIS software to calculate the erosion amount (Fig. 9), the erosion amount was 262 cubic meter in the prototype.

The accumulated soil erosion amount changing curve is shown in the graph (Fig. 10). It can be concluded that the soil erosion increased with the time. And the increase process was in accordance with the sediments contraction process, the curve raised rapidly in the early 25 minutes and then gradually raised to the stabilization later.

Also, it can be inferred that, 5 experiment group results were the same with the prototype, and the experiment conditions are listed in Table 5.

Different rainfall intensity and rainfall lasting time groups could meet the erosion similarity requirement, however, the erosion process in the prototype was complex and full of randomness. It was necessary to make a future verification on the similarity of the typical sections of the terraced field.

According to the measured erosion topographic map of the prototype, 3 typical cross sections were chosen to be verified (Fig. 11). From the comparison of the first cross section, which was close to the ridge, it can be seen that the depth of the erosion gully raised with the rainfall intensity raised. The depth was about 4 m when the rainfall intensity was 3.3 mm/min, 4.2 mm/min and 5.9 mm/min, and the gully depth was only about 3.2 m when rainfall intensity was 0.8 mm/min and 1.25 mm/min (Fig. 12). But, the breadth of the erosion gully was in contrary with that, and it turned to be 6-7 m on low rainfall intensity and 4-5 m on high rainfall intensity. It indicated that the large flow had more effect on the down-cutting process, and the low flow had more effect on the lateral-cutting process. It can also be inferred that the first cross section of the terraced field model could fit the prototype section best on the experiment condition of the rainfall intensity of 1.25 mm/min.

The average depth in the second cross section was about 2.7 m, lower than the first cross section obviously. The average breadth was about 7-8 m, larger than the first section. To be same with the first section, the model second cross section could fit the prototype section best on the experiment condition of the rainfall intensity of 1.25 mm/min (Fig. 13).

The depth of the third cross section declined continuously to 2.2 m, and the breadth reached to 7-9 m. To be same with the two section, the third cross section fitted best on the experiment condition that the rainfall intensity was 1.25 mm/min (Fig. 14).

Based on the verification of the three typical cross sections, it could be inferred that the model erosion topography fitted the prototype topography on the experiment condition that the rainfall intensity was 1.25 mm/min (0.4 mm/min, 0.99 l/s, 161 min in the model).

The experimental results revealed that the erosion process of the prototype in extreme rainstorm could be reappeared under the experiment condition that the rainfall intensity was 0.395 mm/min and the experiment lasting time was 2.68 hours. Both, the erosion amount and the erosion gully topography of the scale model could be verified by the measured data of the prototype. It could be inferred that the equivalent erosive precipitation of the extreme rainstorm was 636 mm. It was an efficient method to research the terraced field soil erosion process and the terraced field construction standard.

CONCLUSIONS

This paper analysed the precipitation frequency according to the rainfall data, constructed the 1:10 scale terraced field model based on the similarity theory, designed the artificial rainfall and water draw experiment, and simulated the terraced field erosion process in extreme rainstorm. The main conclusions are listed as follows.

1. The total precipitation of the 2013 Yan'an extreme rainstorm was 1000.9 mm. The rainfall frequency was less than 0.01.
2. The terraced field model velocity and sediments contraction changing tendency, both appeared to be increasing rapidly early and then fluctuating stability later, which was consistent with the previous research on the rill erosion.
3. The experimental results revealed that both, the erosion amount and the erosion gully topography of the scale model, could be verified under the experiment condition that the rainfall intensity was 0.395 mm/min and the experiment lasting time was 2.68 hours. It can be inferred that the equivalent erosive precipitation of the extreme rainstorm was 636 mm.
4. The 1:10 scale terraced field model could reappear the prototype terraced field erosion process in extreme rainstorm, and it was an efficient method to research the terraced field soil erosion process and the terraced field design standard.

ACKNOWLEDGMENT

This paper was supported by Natural Science Foundation of China (41371276), National Technology Support Project (2011BAD31B05), the Subject of National Science and Technology Major Project (2009ZX07212-002-003-02) and Knowledge Innovation Project of Institute of Soil and Water Conservation, CAS & MWR (Soil and Water Conservation Project) (A315021304).

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