Experimental Study on the Dynamic Process of Runoff Erosion in the Loessial Area

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Abstract: As one of the most eroded areas in the world, the main topographic characters on the Loess Plateau is steep slope and deep gully, with most slope gradient over 15°. To discuss the flow dynamic characters and the soil erosion and sediment production features on steeper slope, simulation studies of runoff scouring on flumes was adapted to study the flow dynamic characters (flow velocity, shear stress and energy consumption) and the soil erosion and sediment production features on steeper slope. The results indicated that there was no simple linear relation between the flow dynamic characters and the soil erosion and sediment production and slope gradient, while the slope gradient is over certain value (in this study, its 24 or so), the flow dynamic characters and the soil erosion and sediment production decreased with the increase of the slope, which demonstrated that there exists a kind of threshold value of the slope gradient to change the flow dynamic characters and the soil erosion and sediment production. Further studies on the relation between soil erosion and slope gradient are of great importance to resuming farmland for trees and grass and the ecological construction in the West.
Keywords: steep slope, flow hydro-dynamic characters, soil erosion and sediment production, critical slope gradient

1   Introduction

Water erosion and soil loss is one of the most urgent problems facing the world, especially to the developing countries. Serious soil and water loss has been the main limiting factors for the agriculture development and ecological construction. The developing process of soil erosion on the steep slope can be divided into interrill erosion, rill erosion and channel erosion, whose initiation & development and effect on sediment production is the key of soil erosion on hill slope. Numerous studies have verified that the qualitative change in sediment production was determined by the initiation of rill erosion. Thus rill erosion was always the main point in soil erosion study. What's more, interactions among topography, overland flow and raindrop splash made the studies of rill erosion complex and diverse. Currently, studies of initiation & development of the rill erosion was mainly followed theories in hydraulics and hydrology, of which neglected the obvious differences in soil, gradient and momentum between the sheet flow transport and flood transport. In 1970s, more effort was focused on the critical conditions of rill erosion occurred and erosion motive power, in which such parameters as gradient, shear stress and soil anti-shear stress were applied. However most researches were carried out on gentle slope, little was known on steep slope, especially the changes of flow hydrodynamic characters under series slope gradient.

In this study, experiments were carried out smooth glass flume and soil scouring flumes respectively to study runoff hydrodynamic characters and changes of soil erosion under series of slope gradient.

2   Materials and method

2.1   Smooth flume experiment

Experiment was carried out on smooth glass flume of 400cm long, 50cm wide, with its gradient easily monitored from 0° to 90°. Runoff discharge was controlled by fixing water head, which was

achieved by fixing valve to control runoff discharge on the upper end of the flume. Sheet flow velocity was measured by electrode method based on the saline solution tracing after the runoff was in steady condition. Experiments with discharge of 0.2L/min, 0.3L/min and 0.4L/min on 15°, 20° and 25° slope respectively were lasted for 5min—10min, each with one duplicate.

2.2 Runoff scouring experiment

Runoff scouring experiments were carried out on steel soil scouring flumes of 33cm wide, 400cm long, and 50 cm deep, of which the gradient was easily tune up. Natural sand of 20cm thick was laid on the floor of the flume, upon which loess was filled by layers after sieved by 1cm. Soil density was near 1.3g/cm^3. Before experiment, water was spread evenly on soil to insure it was saturated. Flow velocity on different section was determined by dying tracing method, and its width was measured on fixing point. Experiments with discharge of 2.5L/min, 3.5L/min 4.5L/min, 5.5L/min and 6.5L/min on 15°, 18°, 21°, 24°, 27° and 30° slope respectively were lasted 15 minutes, each with one duplicate. Component of the experimental soil particles was shown in table 1.

**Table 1   The component of the experimental soil particles**

Particle diameter (mm)	1—0.25	0.25—0.05	0.01—0.005	0.05—0.01	0.005—0.001	<0.001
Percent (%)	0.12%	2.70%	6.88%	41.13%	12.89%	36.28%

3   Results and discussion

3.1   Flow velocity distribution on smooth flume

Results from glass flumes indicated that flow velocity on slope was not increased proportionally from the upper end to the bottom end of the flume, while it was fluctuant along the slope.
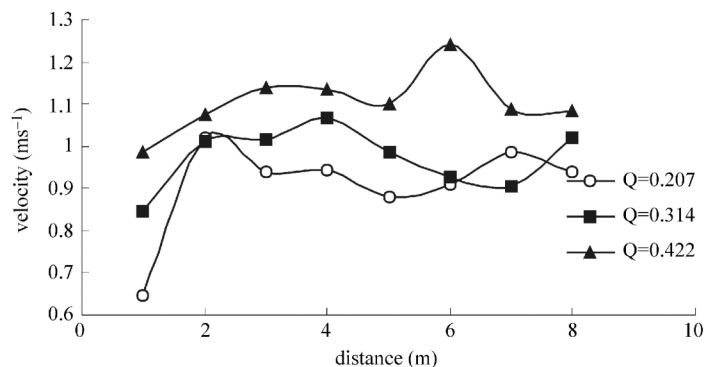
Generally, flow velocity increased with runoff discharge on the same slope, while flow velocity increased with the increase of slope of the same runoff discharge (Fig.1, 2). Sheet flow on steep flow moved in the form of roll waves, which was superposed continuously along downslope, and was affected by unit runoff discharge. The effect of raindrop splash on sheet flow was related to sheet flow depth, slope and raindrop energy (Fig.3).
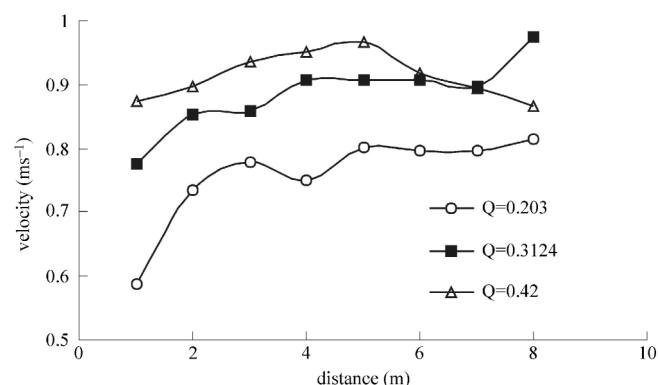

Fig.1   The distribution of the velocity along slope with the different runoff discharges(16.5°)

Based on the indoors experiments and observations in the field, in could be concluded that the development of rill erosion can be divided into different stages. At the initial stages, rill erosion was erosion holes on the slope distributed evenly, which gradually run through each other by erosion tracing to the source.

As the runoff moved forward in roll waves, the connection point of wave crest and wave trough should have regular distribution when the flume surface is smooth, that is they should be distributed evenly at the intervals of wavelength on the slope (Fig.3). On the connecting point, the potential energy entirely converted into kinetic energy, which increased local soil erosion. And when the soil erosion strength exceeded local soil anti-erodibility, erosion holes will be formed, that is the start of rill erosion.

Fig.2   The distribution of the velocity along slope with the different runoff discharges(27°)
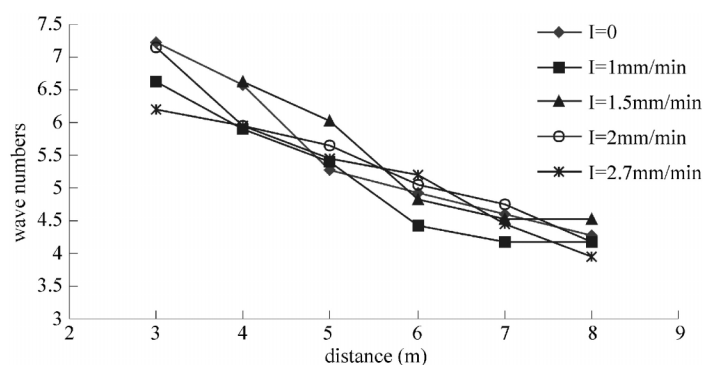
Fig.3   Changes of wave numbers along slope

3.2   Changes of flow velocity on soil flumes

Generally, flow velocity increased with the increase of slope (Fig.4), and this can be explained by the increase component of gravity along the slope surface when slope gradient increase, which drove the flow move faster. With the increase of runoff discharge, flow velocities have no remarkable increase. However, there is a little decrease in flow velocity with larger discharge (4.5L/min, 5.5L/min and 6.5L/min) on steeper slope (30°); it needs further studies and discussions.
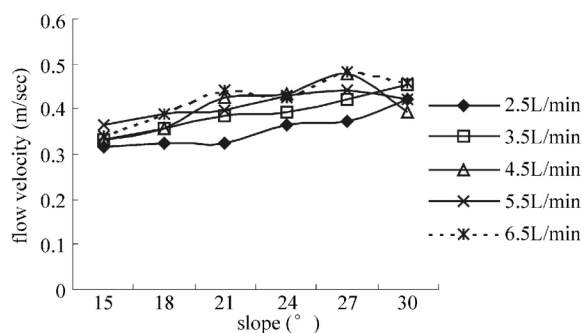
Fig.4   Changes of flow velocity on soil flumes

3.3   Changes of flow energy consumption of different slope and discharge

As the flow potential energy gradually converted into kinetic energy in the runoff process, flow velocity increased. At the same time, part of the flow energy would be lost due to starting soil particle, transporting sediment *etc*, which is the flow energy consumption. Energy consumption process in the interface of soil and water can be calculated according to the law of energy conservation and flow parameters such as flow velocity, runoff discharge and so on.

Generally, flow energy consumption increased with the increase of runoff discharge. On the same slope, as bigger runoff discharge with bigger energy accelerated soil erosion, energy consumption also increased. To the same runoff discharge, runoff energy consumption decreased after increase, like a parabola (Fig 5). And the maximum critical energy consumption value was occurred between 21° to 24°.
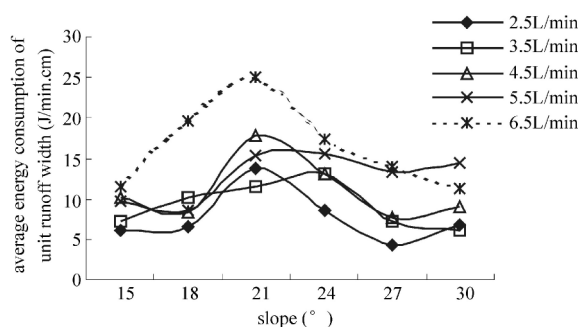

Fig.5   Changes of flow energy consumption of different slope and discharge

Commonly, bigger runoff discharge with bigger energy accelerated soil erosion, and its energy consumption also increased. But in this experiment, component of gravity along slope increased with the slope increase, and decreased soil particles stability, which may need less energy to start the particle and resulted less energy consumption. From Fig 5, flows energy consumption increased before 21°, while decreased when slope exceeded 24°. Thus it can be concluded that the critical energy consumption value occurred between 21° to 24°. Also, there was little difference in critical slope value as runoff discharge changed, it may relate to the effect of slope and runoff discharge on flow energy, and soil erodibility etc..

3.4   Changes of sediment transportation ratio of per unit discharge width

Generally, it can be concluded from Fig. 6 that the runoff sediment transportation ratio increased with the increase of runoff discharge, while its changes with slope looked like parabola. Based on former analysis, the relation between sediment transportation ratios of unit runoff width runoff discharge was similar to that between energy consumption and runoff discharge, which indicated that there existed close relation between runoff sediment transportation and energy consumption.
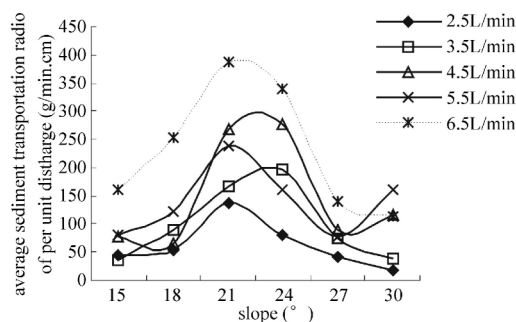
Fig.6   Changes of sediment transportation ratio of per unit discharge width

After analysis relation between sediment transportation ratios of unit runoff and energy consumption of unit runoff, shear stress of unit runoff respectively, following equations can be got:

$$Wr = 28.375(\tau - 1.757) \qquad\qquad R^2 = 0.870 \qquad\qquad (1)$$

$$Wr = 19.117(\Delta E - 3.016) \qquad\qquad R^2 = 0.936 \qquad\qquad (2)$$

Where Wr is sediment transportation ratios of unit runoff; τ is shear stress of unit runoff; and ΔE is energy consumption of unit runoff. It is easily concluded that there existed obvious linear relation between sediment transportation ratios of unit runoff and energy consumption of unit runoff, shear stress of unit runoff respectively, and the critical shear stress and critical energy consumption value when rill erosion occurred were 1.757 Pa/(min • cm) and 3.016 J/(min • cm) respectively. Only when the shear stress and energy consumption exceeded such value, can it be possible for rill erosion occurred. What's more, the correlation coefficients of equation (2) is higher than that in equation (1), which indicated that it was better in describing runoff and sediment production on slope.

4   Conclusions

(1) The results indicated that flow velocity fluctuated along slope: it increased with the increase of runoff discharge and slope; runoff moved in roll waves and superposed continuously down slope.

(2) Changes energy consumption of unit runoff discharge looks like parabola, similar trends existed in the changes of flow runoff sediment transportation of unit runoff discharge, which indicated that there existed critical slope in soil erosion. In this experiment, the critical slope was between 21° to 24°.

(3) There existed obvious linear relations between sediment transportation ratios and energy consumption of unit runoff, between sediment transportation ratios and shear stress of unit runoff respectively; modeling results indicated that energy consumption was better in describing flow erosion and sediment production process on slope.

References

[1] Abrahams AD, Parsons AJ. Determining the mean depth of overland flow in field studies of flow hydraulics. Water Resource Research, 1990, **26** (3): 501-503.
[2] Chi-hua Huang, Joe M.Bradford, J.M.Laflen. Evaluation of the detachment-transport coupling concept in the WEPP ril erosion equation. Soil Sci Soc Am Jour, 1996 60:734-73.9.
[3] Gang Li, A.D.Abrahams. Correction factors in the determination of mean velocity of overland flow. Earth surface Process and Landforms, 1996, 21:509-515.
[4] Julien PY, Simons DB. Sediment transport capacity of overland flow. Transaction of the ASAE, 1985 28(3):755-762.
[5] Lei Alin, Tang Keli. Kinetic condition of rill erosion on Loess sloping face. Journal of Soil Erosion and Water Conservation. 1998, **4** (3):39-43.
[6] Moore ID, Burch GJ. Sediment transport capacity of sheet and rill flow: application of unit stream power theory. Water Resource Research, 1986, **22** (8): 1350-1360.
[7] Parsons AJ, Abrahams AD, John Wainwright. On determining resistance to interrill overland flow. Water Resource Research, 1994, **30** (12): 3515-3521.
[8] Zhang Guanghui. Advances in study of runoff detachment process based on hydraulic. Advances in Water Science, 2001,**12**(3):395-402.
[9] Zhang Keli, Akiyoshi Yasuhiro. Critical hydraulic condition of rill erosion on sloping surface. Journal of Soil Erosion and Water Conservation. 1998, **4** (1):41-46.