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Original Research Paper

Dynamic Mechanics of Soil Erosion by Runoff on Loess Slope

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ABSTRACT

In this research, soil erosion and sediment yield were calculated by runoff shear stress, runoff energy consumption and runoff power theory. Results indicated that a linear relationship existed between the average runoff shear stress and sediment yield. Soil erodibility in the experiment was 178.5g/(Pa·min), and the critical shear stress value was 0.54 Pa. Results from energy consumption implied that there was also a linear relationship between sediment transportation and energy consumption of runoff unit width: Dr = 14.61 (ΔE-0.37), which indicated that the soil erodibility was 14.61g/J, with a critical energy consumption of 0.37J/(min·cm). Results from runoff power theory showed that sediment transportation increased with increase in runoff power, and the simple linear relationship was also regressed: Y = 8942.2x - 68.676. Generally, these three theories each showed certain advantages in describing the soil erosion processes on the slope, among which the results from energy consumption theory were simpler, more accurate, and proved more convenient in describing soil erosion on the slope.

INTRODUCTION

Excessive soil erosion by water is a worldwide concern that degrades soil quality, causes loss of productivity, loss of plant nutrients, and off-site environmental problems, such as sedimentation in streams and water reservoirs. Rill erosion, which results from concentrated flow in a limited and confined space, is a critical component of the erosion system in upland areas (Li et al. 2001). Therefore, during the past decades, studies on the physical mechanism and development processes of rill erosion have received widespread attention from researchers all over the world (Foster & Meyer 1975, Govers 1990, Knisel 1980, Nearing et al. 1989, Laflen et al. 1991, Li et al. 2001). Numerous equations describing the relationship between rill detachment rate and the average hydraulic shear stress of flowing water in the rills have been proposed (Meyer & Wischmeier 1969, Foster & Meyer 1975, Nearing et al. 1989, Laflen et al. 1991, Foster & Meyer 1977, Foster 1982, Lei & Tang 1998, Gilley et al. 1990). Foster et al. (1984), Knisel (1980), Laflen et al. (1991), Meyer et al. (1985), and Foster & Meyer (1975) proposed that, soil detachment from a rill perimeter was primarily a function of the average shear stress of flowing water in the rills. The following equation or similar is used to calculate the soil detachment rate in a rill: $D_r = K_\tau(\tau-\tau_c)^n$

However, results from Foster et al. (1984), Tingwu Lei & Nearing (1998) and Nearing et al. (1998) indicated that water flow in the rills was non-uniform because of non-uniformities of both the channel cross-section and bottom profile along the rill. Consequently, shear stress from grain roughness in the rill varied with location. Intense local velocities and shear stresses in a rill appear to cause large local erosion rates. In addition, since the flow in the rill was turbulent, instantaneous shear stress from grain roughness fluctuated with time (Foster et al. 1984). This spatial and temporal variation in shear stress distorts parameter values in erosion equations involving critical shear stress, such as the one mentioned above. At the front of the wave, the flow depth and hydraulic slope gradient are several times that of the uniform flow. Therefore the shear stress ($\tau = \gamma hJ$) in the front of the wave will be several times than that of the uniform flow. Then the shear stress distribution along the down-slope will fluctuate sharply. Thus, using a constant average hydraulic shear stress as an overall predictor for rill detachment does not consider the spatial and temporal variation of shear stress in the rills.

It is recognized that the process of soil detachment through flowing water in the rills is a process of dissipation of flow energy. In recent years, researchers (Li et al. 2001) proposed that the process of soil erosion could be treated as a complicated process of energy conversion and redistribution. The greater the flow energy consumed, the more soil particles are detached and transported. Thus, soil erosion by water is a process of detachment and transportation of soil material by erosive water (Ellison 1947) and must be in accordance with the law of energy conservation. Therefore, a relationship between flowing water and soil particles eroded or to be eroded can be determined along with a relationship between amount of erosion and runoff energy consumption.

Since soil erosion by runoff is a process of energy consumption, it is also possible to express soil erosion in terms of power. Yang (1973) defined unit runoff power as the product of flow rate and gradient. In his view, power consumed in the course of sediment transportation is directly related to the power of the unit water body. Moor & Burch (1986) tried Yang Zhida's (Yang 1973) theory in calculating the rill erosion over slope. Results indicated that Yang Zhida's formula is able to accurately predict the sediment transportation ratio of flow on the slope and in the rill.

To compare the difference in soil erosion prediction by different theories, and to help understand the dynamic process of erosion, runoff scour simulation was carried out to analyse the relationship between runoff shear stress, runoff energy consumption, unit runoff power and soil erosion under different slope and runoff discharge conditions. This paper focused on: (1) soil erosion dynamics under different runoff discharge and slope; (2) setting up a statistical or mathematical model to calculate soil erosion on the slope; and (3) comparing the difference in soil erosion described by the different theories.

MATERIALS AND METHODS

The experiment was conducted in a steel gradient adjustable flume, 4 m long, 0.33 m wide and 0.8 m deep. The flume soil bed was prepared in two stages. In the first stage, a 20 cm-thick sand layer was placed on the bottom of the flume to provide natural infiltration conditions for the experimental soil. In the second stage, another 20 cm-thick layer of soil, sieved to pass a 1 cm screen was packed on top of the sand layer, which was separated by gauze from the soil. The dry bulk density of the soil in the flume was controlled at about 1.25g/cm^3. In order to keep the initial condition of every experiment as consistent as possible, before the start of the scouring experiment, water was sprinkled uniformly on the surface of the slope until the soil attained sufficient saturation. Runoff discharges in the experiments are 2.5 L/min, 3.5 L/min, 4.5 L/min, 5.5 L/min and 6.5 L/min. During the experiment, the sediment concentration was determined by collecting the sediment sample every minute in the flume outlet. Meanwhile, the velocity of flow on the slope was measured by using a dying trace method, and runoff width was measured using a ruler. The experiment lasted for approximately 15 minutes. Ten slope gradients (3°, 6°, 9°, 12°, 15°, 18°, 21°, 24°, 27° and 30°) were adopted. Soil used in the experiment is from loess parent substance of "lou tu" in Yangling, and its particle composition is listed in Table 1.

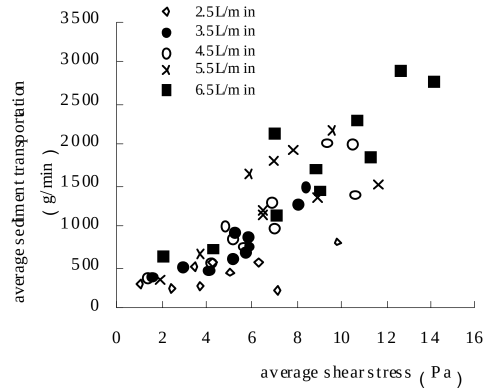

Fig. 1: Relationship between average shear stress and average sediment transportation.

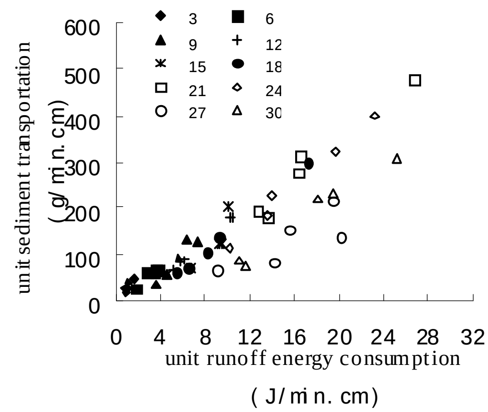

Fig. 2: Relationship between unit width runoff sediment transportation and unit width runoff energy consumption.

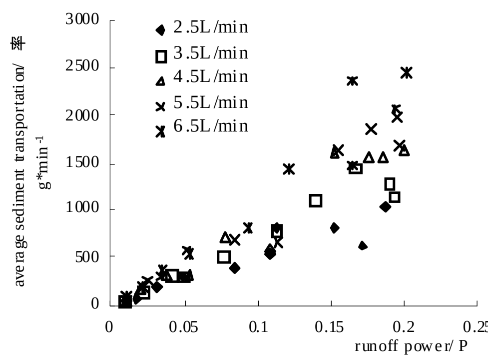

Fig. 3: Relationship between runoff power and average sediment transportation.

RESULTS AND ANALYSIS

Relationship between runoff shear stress and soil erosion: Runoff shear stress on the soil-water interface helps to remove adherence between soil grains, releasing and separating the grains, and consequently provides a substantial means of erosion and runoff transportation. The greater the runoff

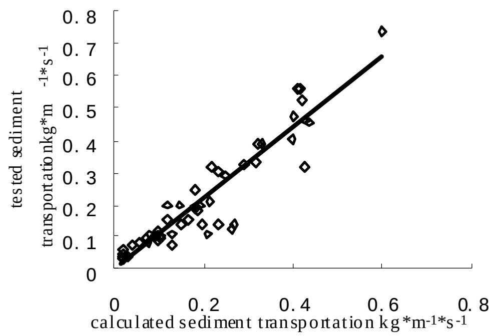

Fig. 4: Comparison of predicted and tested sediment transportation by unit unit runoff power theory.

shear stress, the more effective the shear stress over soil will be, and the more the soil is separated, the greater the erosion will be. Observation shows that in most cases, due to the steepness of the slope and high runoff speed, little sediment deposition occurred on the slope.

Fig. 1 shows the relationship between average shear stress and average sediment transportation under different gradients and runoff. From Fig. 1, it was clear that a linear relationship exists between the average sediment transportation and average runoff shear stress under different water flow situations, and the greater the average shear stress is, the greater the average sediment transportation will be. Since there is very little sediment deposited in the experiment, the following formula is proposed for this relationship:

$$D_t = k(\tau\text{-}\tau_c) \quad ...(1)$$

where D_t is runoff sediment transportation (g/min); τ is runoff shear stress (Pa); τ_c is critical runoff shear stress (Pa); k is soil erosion resistance parameter (g/Pa.min). Statistical analysis on the average shear stress and average sediment transportation under different gradients and runoff discharge indicated that the following equation existed:

$$D_t = 178.5(\tau\text{-}0.54) \qquad R^2 = 0.78 \quad ...(2)$$

(Symbols refer to the previous formula)

Formula (2) shows that the soil erosion resistance parameter tested is 178.5g/ (Pa.min) and the critical runoff shear stress is 0.54 Pa, which indicates that erosion only occurs when runoff shear stress exceeds 0.54 Pa. Analysis on the simulated data indicated that the correlation index in formula (2) is relatively high ($R^2 = 0.78$), and this formula may be used for calculating and analysing soil erosion under given runoff shear stress.

Relation between runoff energy consumption and soil erosion: The theory of runoff energy consumption is in fact a black box process operation; it uses the original and final situation in the erosion process to calculate runoff energy consumption, other factors, such as when, where, and how the energy was consumed, are neglected. In this way, we need not take the complicated process of erosion into consideration. Only changes of flow rate, runoff and gradient are used in this theory.

Based on the law of energy conservation, Li et al. (2001) proposed the concept of critical energy consumption which was established after analysing and deducing the runoff energy consumption process in the flume, based on the quantitative relationship between runoff energy consumption and erosion. It is as follows:

$$Dr = k(\Delta E - E_c) \quad ...(3)$$

Where Dr is the runoff sediment unit width transportation (g/min·cm), k is the soil erodibility parameter (g/J), ΔE is the energy consumption of unit width runoff (J/min·cm), and E_c is the energy consumption of critical unit width runoff (J/min·cm). This formula is significant from a physics perspective, that is, under certain experimental conditions, the occurrence of rill erosion is related to critical runoff energy consumption, and the sediment transportation of unit runoff width is directly related to the energy consumption of unit runoff that exceeds the critical runoff energy consumption.

Fig. 2 reflects the relationship between sediment transportation and runoff energy consumption of unit runoff width in the experiment. From Fig. 2, the linear relationship existed between sediment transportation and energy consumption of unit runoff width under different gradients and discharges. In Fig. 2, the beeline slope represents the erodibility parameter of the soil, and the intercept is the product of erodibility and critical energy consumption. The slope and intercept differ with gradient. There are two reasons for this: first, the component of gravity force along the slope is different due to the steepness, which leads to a difference in energy requirement for starting sediment; second is the difficulty in maintaining consistency when filling the flume for different slopes and discharges, which leads to a difference.

Based on the experimental data, following equation can be deduced by mathematical analysis:

Table 1: Grain size of experiment soil.

Grain Size/mm	1 ~ 0.25	0.25 ~ 0.05	0.01 ~ 0.005	0.05 ~ 0.01	0.005 ~ 0.001	< 0.001
%	0.12	2.70	6.88	41.13	12.89	36.28

$$Dr = 14.61\ (\Delta E\text{-}0.37) \qquad R^2 = 0.84 \qquad ...(4)$$

(Symbols refer to previous formula description)

The formula indicates that the erodibility of tested soil is 14.61 g/J, critical energy consumption of unit width runoff is 0.37 J/min·cm. The parameter of soil erodibility is 14.61 g/J that indicates to the tested soil, every 1 J energy consumed in the scouring may wash off 14.61 g of soil. The critical energy of unit runoff width implies that erosion only occurs when the energy consumption of unit width runoff exceeds 0.37 J/min·cm.

Relationship between runoff power and soil erosion: Based on the experimental conditions and experience from Moor & Burch (1986), sediment yield of unit width runoff is calculated by runoff power theory. According to the coincidence between the observed and calculated data, the possibility of runoff power theory for erosion calculation on the slope was analysed.

A chart of the relationship between runoff power and average sediment transportation (Fig. 3) has been drawn using the result calculated with runoff power theory and the data tested. Results indicate that a linear relationship existed between runoff power and runoff average sediment transportation, where the runoff sediment transportation increased with increasing runoff power. The linear relationship was drawn as follows using statistical analysis:

$$Y = 8942.2x - 68.676 \qquad R^2 = 0.80 \qquad ...(5)$$

Fig. 4 reflects the relationship between the calculated and observed data. From Fig. 4, we can see a linear relationship between the calculated and observed data, which can be illustrated by the following linear formula:

$$W_s = 0.9424W_p - 0.0086 \qquad R^2 = 0.86 \qquad ...(6)$$

Where W_s is the tested data and W_p is the calculated data. Although certain differences exist between the calculated and observed sediment by runoff, these two data series show a high correlation, which indicate that unit runoff energy consumption theory can be used to calculate soil erosion on the slope, when provided with runoff discharge, steepness, etc.

Comparison of soil erosion dynamics from different theories: Based on the above analysis, three theories involving runoff shear stress, runoff energy consumption, and unit runoff power, showed possibilities for describing the power process of erosion.

From runoff shear stress theory, we know that shear stress is calculated from the runoff average water depth, which represented the average situation of runoff. In fact, the runoff distribution along the slope is unbalanced in the process of soil erosion. There will be some points where water depth exceeds the average value, thus runoff shear stress on these points must exceed the average runoff shear stress, and consequently soil erosion tends to increase. Thus, there must be some errors in the calculation of soil erosion and the description of the erosion process when using runoff shear stress theory, as the unbalanced distribution of runoff erosivity along the slope was neglected.

From the view of runoff energy consumption theory, the erosion process on the slope is also a process of energy transformation, in which potential energy is translated into kinetic energy and energy for soil grain separation and transportation. By using this theory, such errors from the average value in runoff depth and shear stress can be avoided. Runoff energy consumption theory is concerned with the original situation and final situation only, both physically and temporally. So during the soil erosion process, energy consumption by erosion may be calculated and compared by calculating the runoff energy difference between the top and lower ends in terms of the relative height and runoff velocity. However, further efforts are still needed to improve this theory. One issue is improving the accuracy in velocity measurement and the other is a detailed description of energy consumption in the erosion process along the slope. Thus, further research should be conducted by integrating theories from hydraulics, mechanics of sediment transport, etc. to further improve the theory.

Originally, unit flow power theory is applied to flows in open channels. Experiments from Moor and Burch (1986) verified that it could be used for describing the process of erosion. Although unit runoff power theory provides an effective way for describing soil erosion processes, its application in soil erosion research needs further practice and improvement, as this theory is less practised in soil erosion research, and more detailed research should be prepared to determine parameters such as critical unit water flow power for different soil types.

To summarise, all three theories mentioned above had their advantages in describing soil erosion dynamics and processes. Generally, the theory of runoff energy consumption is better in describing the process of soil erosion as it is more convenient and accurate. The results of our research also indicated that the correlation index between runoff unit width sediment transportation, and unit width runoff energy consumption is the highest of the three.

CONCLUSIONS

In this paper the dynamics of soil erosion on the slope was calculated and analysed by the theory of runoff shear stress, runoff energy consumption, and runoff power. The following conclusions can be drawn:

A clear linear relationship exists between the runoff average sediment transportation and runoff average shear stress in the following formula: Dt = 178.5 (τ - 0.54), which indicates that the soil resistance parameter tested as 178.5 g/(Pa·min), and the critical runoff shear stress as 0.54 Pa.

A linear relationship also exists between the unit runoff sediment transportation and unit runoff energy consumption, as illustrated by the following formula: Dr = 14.61 (ΔE-0.37). Results indicate that the erodibility of the tested soil was 14.61 g/J, and the critical energy consumption of unit runoff width was 0.37 J/ (min·cm), that is, the critical dynamic for erosion occurrence is 0.37 J/min.cm.

Runoff sediment transportation increases with the increase of runoff power. A clear linear relationship exists between the average runoff sediment transportation and runoff power, which can be illustrated as Y = 8942.2x – 68.676, with a high correlation between calculated and observed data.

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REFERENCES

Ellion, W.D. 1947. Soil erosion studies, part I. Agricultural Engineering, 28(4): 145-146.

Foster, G.R. and Meyer, L.D. 1975. Mathematical simulation of upland erosion by fundamental erosion mechanics. In: Present and Prospective Technology for Predicting Sediment Yields and Sciences, 190-207, ARS-S-40, Washing DC:USDA-Science and Education Administration.

Foster, G.R. and Meyer, L.D. 1977. An erosion equation derived from basic erosion principles. Transactions of the ASAE, 20(4): 678-682.

Foster, G.R. and Meyer, L.D. 1972. Transport of soil particles by shallow flow. Transactions of the ASAE, 15(1): 99-102.

Foster, G.R., Huggins, L.F. and Meyer, L.D. 1984. A laboratory study of rill hydraulics: I. Velocity relationships. Transaction of the ASAE, 27(3): 790-796.

Foster, G.R., Huggins, L.F. and Meyer, L.D. 1984. A laboratory study of rill hydraulics: II. Shear stress relationships. Transaction of the ASAE, 27(3): 797-804.

Foster, G.R. 1982. Modeling the erosion process. In: Hydrologic Modeling of Small Watersheds, Edited by C.T. Haan et al., ISB No-916150-44-5, pp. 295-380.

Foster, G.R., Meyer, L.D. and Onstad, C.A. 1977. An erosion equation derived from basic erosion principles. Transactions of ASAE, 20(4): 678-682.

Govers, G. 1990. Empirical relationships for the transport capacity of overland flow: Erosion, transport, and deposition process, IAHS Publ., 189: 45-63.

Gilley, J.E., Kottwitz, E.R. and Simanton, J.R. 1990. Hydraulic characteristics of rills. Transactions of ASAE, 33(6): 1900-1906.

Knisel, W.G. (ed.) 1980. CREAMS: A field-scale model for chemicals, runoff and erosion from agricultural management systems. Conservation Research Report No.26., Washington DC, USDA - Science and Education Administration.

Laflen, J.M., Elliot, W.J., Simanton, J.R., Holzhey, C.S. and Kohl, K.D. 1991. WEPP soil erodibility experiments for rangeland and cropland soils. J. Soil and Water Conservation, 46(1): 39-44.

Lei Alin and Tang Keli 1998. Kinetic condition of rill erosion on loess sloping face. Journal of Soil Erosion and Soil and Water Conservation, 4(3): 39-43.

Li Zhanbin, Lu Kexin and Ding Wenfeng 2001. Study on the dynamic process of rill erosion on loess slope surface. International Journal of Sediment Research, 16(1): 308-314.

Meyer, L.D. and Wischmeier, W.H. 1969. Methematical simulation of the process of soil erosion by water. Transactions of the ASAE, 12(6): 754-758.

Moor, I. P. and Burch, G. I. 1986. Sediment transport capacity of sheet and rill flow: Application of unit stream power theory. Water Resources Research, 22(8): 1350-1360.

Nearing, M.A., Foster, G.R., Lane, L.J. and Finkner, S.C. 1989. A process-based soil erosion model for USDA- water erosion prediction project technology. Transactions of the ASAE, 32(5): 1587-1593.

Ting Wu Lei and Mark A. Nearing 1998. Rill erosion and morphological evolution: A simulation model. Water Resources Research, 34(11): 3157-3168.

Yang, C.T. 1973. Incipient motion and sediment transport. Journal of the Hydraulics Division, ASCE, 99: 919-934.

Zhanbin Li, Mingan Shao, Zhanli Wang and Bing Shen 1999. Modeling on the inter-rill erosion in the Loess Plateau of China. International Journal of Sediment Research, 14(2): 319-324.