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# Modeling on Tillage Erosion in Loess Region of China

Wang Zhanli, Shao Ming'an
(*Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling* 712100, *China*)

**Abstract**: Tillage erosion is a new field of soil erosion research. To quantitatively describe processes of tillage erosion in loess region of China, this paper modeled the tillage erosion here by conducting tillage experiment, in which small cubes were used as the tracers to trace and monitor soil movement, and regressive and theoretical analyses, and developed the model of tillage erosion with which net erosion modulus at any point of slope profile can directly be calculated. The results showed that in the case of across2slope tillage operation of come2and2go single pass along contour line from down2slope to up2slope in which the soil was turned down2slope with local traditional plow pulled by animal power: (1) Mean horizontal distance of soil displacement per tillage operation in slope aspect direction is linearly related to slope gradient; (2) The net erosion modulus at any position of slope profile per tillage operation is affected by soil bulk density, tillage depth, coefficient determined with soil and tillage conditions, and topography curvature.

**Key words**: loess region of China; tillage erosion; modeling; horizontal displacement distance; net erosion modulus; topography curvature

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## 1 Introduction

It has been known that soil erosion can result in soil degradation, water pollution and many consequences associated with sediment yield, etc. Many scientists, governments and related organizations in the world have paid great attention to research and control on soil erosion since 20th Century. But all of these efforts were mainly focused on water erosion. Nearly one decade, some researches showed that erosion by tillage may be comparative with erosion by water, and even more intense than water erosion on much of cultivated land[2, 4, 5].

The hillslope of arable land in China is shorter, steeper and more ragged than that in many other countries, especially the Western developed countries. Therefore, tillage erosion is an important type of erosion in China. To get knowledge of processes, intensities, features and impacts, etc. of tillage erosion in China, we initiated a study of the loess region of China. This paper reports a partial result of this research project.

Lindstrom et al. (1992, 2000) and Govers et al. (1994) studied the model of tillage erosion. In this paper, an empirical model of distance of soil redistribution by tillage was established by conducting tillage experiment in which small cubes were used as tracers, based on which the model of tillage erosion was then theoretically developed in the Loess Plateau of China where soil erosion is the most intense throughout the world in order that the net erosion modulus at any point of slope profile can directly be calculated.

## 2 Materials and Methods

The experiment was conducted in the Ansai County, Shaanxi Province, located in the center of the Loess Plateau where topography belongs to the typical hilly and gully region and also is of

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Biographies: Wang Zhanli (1960- ), male, associate professor; Shao Ming'an (1956- ), male, Ph. D. professor.

representative features in loess region of China, relative height differences mostly are 150～200 m, gully density is about 8 m/km$^2$, and percentage of incised land areas to total land areas is about 60%, which explains that more than half land here is encroached by gullies. The experimental slope-land is concave up-slope and convex down-slope with the elevation of about 1430m, slope length of 40m, slope aspect of nearly facing east, the maximum slope gradient of about 30°, the minimum slope gradient of 0°, and lateral slope gradient of 0°. The soil here is loess soil developed in loess parent material with even texture which mainly consists of silt whose contents are 53.9%～74.8%. The crop cycle here is once per year and main crops are autumn ones. The experimental site has been fallow for one year before our experiment conducted. The soil of tillage layer at the time of experiment is relatively compact, the mean bulk density is 1.3 g/cm$^3$ and the soil moisture is 10.01%.

To obtain distance of soil redistribution by tillage and its variation with slope gradient, and to further develop the model of tillage erosion, small cubes made of organic glass with carved numbers on their surface were used as the tracers to trace soil movement. Each small cube of tracer has a cube of 1×1×1 cm$^3$ and a density of 1.15 g/cm$^3$ which is roughly close to soil bulk density of plough layer.

7 sub-hillslope with slope gradient of 0°, 5°, 10°, 15°, 20°, 25° and 30° respectively were selected on the experimental hillslope from up-slope to down-slope. A rectangular trench with length of 110cm, width of 10cm and depth of 15cm was dug on each sub-hillslope. Small cubes of tracer were installed layer by layer and one by one in every rectangular trench. After tracer cubes on the bottom tracer layer of rectangular trench were installed, the position of each cube was precisely measured with theodolite and range finder, and then the rectangular trench was filled with soil up to the depth of the second tracer layer. The tracer cubes were sequentially installed on the second tracer layer of rectangular trench, and the position of each cube on this layer was again measured in the same way as that on first layer. This was repeated until all tracer cubes were installed and all their position were measured in every rectangular trench. There are 4 layers of tracer in every rectangular trench and 11 tracer cubes on every layer, so that there are 44 and 308 small cubes of tracer in each rectangular trench and in 7 rectangular trenches of all sub-hillslope respectively. The horizontal and vertical spacing between neighbor tracer cubes is 10cm and 5cm respectively. As those were finished, across-slope tillage operation of come-and-go single pass along contour line from down-slope to up-slope was conducted with local traditional plow with plough depth of 16cm and pulled by animal power, and the plowed soil was all turned down-slope. After the tillage operation, all small cubes of tracer were immediately excavated in the plowed soil, and meanwhile positions of all displaced cubes were accurately recorded with theodolite and range finder once more. By checking the amount, the recovered rate of tracer cubes is more than 95% in every rectangular trench of sub-hillslope. Finally, redistribution distance of each tracer cube was obtained by calculation.

## 3 Results and Discussion

Tillage implement and water power can all detach and transport soil. However tillage implement can only transport soil within limited distance and mainly cause on-site soil redistribution unlike water power which can transport soil very far away and cause soil loss on certain site. The distance of soil redistribution by tillage is only affected by slope gradient in the case of certain tillage implement, tillage way and soil. Because slope gradient of natural hillslope is always variable with different positions, the distance of soil redistribution by tillage is also not identical at different positions on hillslope so that erosion will be produced on some positions and deposition will happen on some other positions on hillslope. To model stated rules of soil movement by tillage, the model of variation of distance of soil displacement by tillage with slope gradient need to be studied firstly, on the basis of which model of tillage erosion is further developed.

To establish the model of variation of distance of soil redistribution by tillage with slope gradient, horizontal displaced distance of each recovered tracer cube in slope aspect direction compared with its corresponding original position before tillage was computed and the mean horizontal displaced distance of all recovered tracer cubes in rectangular trench on each sub2section of hillslope was further calculated respectively. The curve of relationship between the mean horizontal displaced distance of all cubes in each sub2hillslope and tangent of slope gradient of corresponding sub2section of hillslope was plotted in Fig. 1. And the regressive analysis showed that the empirical model of variation of the mean horizontal displacement of tillage layer soil per tillage operation with slope gradient is

$$D = -0.2379S + 0.0953 \qquad (1)$$

where $D$ = mean horizontal displacement of tillage layer soil per tillage operation, m; $S$ = tangent of slope gradient whose initial direction is coincident with that of soil horizontal movement, möm; $R^2 = 0.79$; A= 0.01. The regression square and significance level explain that equation (1) is quite reliable.

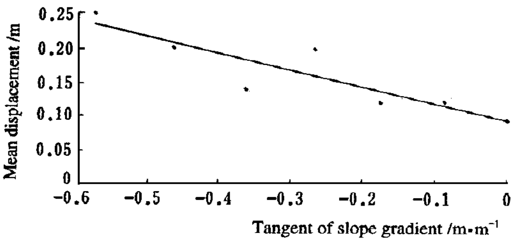


Fig. 1 Relationships between mean horizontal displacement per tillage operation and slope gradient

Equation (1) and Fig. 1 showed that the mean horizontal displacement of tillage layer soil in direction of slope aspect per tillage operation linearly increase by degrees with increase of absolute value of slope gradient. To develop the model of tillage erosion, x2axis was positively oriented in the direction of slope aspect, and z2axis was positively oriented in the direction perpendicu2lar to x2axis and contrary to gravity direction.

It has been obtained by using small cubes as tracers to conduct tillage experiment and successive statistical analysis that the mean horizontal displacement of tillage layer soil in direction of slope aspect per tillage operation is linearly related to slope gradient. This relationship can be expressed with universal equation as

$$D = A + BS \qquad (2)$$

where $D$ = mean horizontal displacement of tillage layer soil per tillage operation, m; $S$ = tangent of slope gradient, i.e. $\frac{\partial z}{\partial x}$, m·m$^{-1}$; $A$, $B$ = regression coefficients, m.

At any point $(x, z)$ on hillslope profile (slope gradient in tillage direction was assumed to be zero), the soil flux per unit width of tillage layer per tillage operation is

$$Q_{(x, z)} = RHD_{(x, z)} \qquad (3)$$

where $Q_{(x, z)}$ = soil flux per unit width of tillage layer at point $(x, z)$ per tillage operation, kgöm; $D_{(x, z)}$ = mean distance of soil displacement of tillage layer at point $(x, z)$ per tillage operation, m; $R$ = mean bulk density of tillage layer soil, kgöm$^3$; $H$ = depth of tillage layer, m.

Combining equation (2) with equation (3) gives

$$Q_{(x, z)} = RH\ (A + BS_{(x, z)}) \qquad (4)$$

where $S_{(x, z)}$ = tangent of slope gradient at point $(x, z)$, möm.

The soil flux per unit width of tillage layer per tillage operation at point $(x + \Delta x, z + \Delta z)$ neighboring with point $(x, z)$ in same direction of horizontal movement is

$$Q_{(x+\Delta x, z+\Delta z)} = RHD_{(x+\Delta x, z+\Delta z)} \qquad (5)$$

where $Q_{(x+\Delta x, z+\Delta z)}$ = flux per unit width of tillage layer per tillage operation at point $(x + \Delta x, z + \Delta z)$, kgöm; $D_{(x+\Delta x, z+\Delta z)}$ = mean horizontal distance of soil displacement of tillage layer at point $(x+\Delta x,\ z+\Delta z)$ per tillage operation, m, or $Q_{(x+\Delta x,\ z+\Delta z)} = RH(A + BS_{(x+\Delta x,\ z+\Delta z)})$ (6)

where $S_{(x+\Delta x,\ z+\Delta z)}$ = tangent of slope gradient at point $(x+\Delta x,\ z+\Delta z)$, m·m.

Subtracting equation (4) from equation (6) gives the increment of soil flux per unit width of tillage layer per tillage operation from point $(x,\ z)$ to point $(x+\Delta x,\ z+\Delta z)$, i.e. the net soil flux per unit width of tillage layer per tillage operation between point $(x,\ z)$ and point $(x+\Delta x,\ z+\Delta z)$ as

$$\Delta Q = Q_{(x+\Delta x,\ z+\Delta z)} - Q_{(x,\ z)} \qquad (7)$$

where $\Delta Q$ = net soil flux per unit width of tillage layer per tillage operation between point $(x,\ z)$ and point $(x+\Delta x,\ z+\Delta z)$, kg·m, or

$$\Delta Q = RH(A + BS_{(x+\Delta x,\ z+\Delta z)}) - RH(A + BS_{(x,\ z)}) \qquad (8)$$

i.e.

$$\Delta Q = RHB\Delta S \qquad (9)$$

where $\Delta S$ = increment of tangent of slope gradient from point $(x,\ z)$ to point $(x+\Delta x,\ z+\Delta z)$, m·m.

Thus mean net soil flux per unit width per unit length of tillage layer per tillage operation between point $(x,\ z)$ and point $(x+\Delta x,\ z+\Delta z)$ is

$$\frac{\Delta Q}{\Delta x} = \frac{RHB\Delta S}{\Delta x} \qquad (10)$$

where $\frac{\Delta Q}{\Delta x}$ = mean net flux per unit width per unit length of tillage layer per tillage operation between point $(x,\ z)$ and point $(x+\Delta x,\ z+\Delta z)$, kg·m$^{2}$.

When $\Delta x \to 0$, the net erosion modulus of tillage layer per tillage operation at point $(x,\ z)$ is given as

$$\frac{\partial Q_{(x,\ z)}}{\partial x} = RHB\frac{\partial S_{(x,\ z)}}{\partial x} \qquad (11)$$

where $\frac{\partial Q_{(x,\ z)}}{\partial x}$ = net erosion modulus of tillage layer per tillage operation at any point $(x,\ z)$ of slope profile, kg·m$^{2}$; $\frac{\partial S_{(x,\ z)}}{\partial x}$ = curvature at any point $(x,\ z)$ of slope profile, m$^{2}$·m$^{2}$.

Substituting $S = \frac{\partial z}{\partial x}$ into equation (11) gets

$$\frac{\partial Q_{(x,\ z)}}{\partial x} = RHB\frac{\partial^2 z}{\partial x^2} \qquad (12)$$

where $\frac{\partial^2 z}{\partial x^2}$ = curvature at any point $(x,\ z)$ of slope profile, m$^{2}$·m$^{2}$.

Equation (12) explains net erosion modulus of tillage layer at any position on hillslope profile per tillage operation is influenced by soil bulk density, depth of tillage layer, other conditions of soil and tillage and topography curvature.

As $R$, $H$ and $B$ in equation (12) are all constants in the case of certain soil and tillage, therefore equation (12) has also explained that net erosion modulus of tillage layer at any position on hill slope profile per tillage operation is only affected by topography curvature at corresponding position. This described rule followed by tillage erosion means that when soil tillage is performed, net erosion and deposition by tillage are not related to slope gradient and slope length included in landform factors; the more irregular and rolling the topography, the more extensive and intense the net erosion and deposition processes by tillage.

Substituting regression coefficient determined with equation (1) into $B$ in equation (12) and taking $C$ and $A$ to respectively express curvature at any point of slope profile and net erosion modulus of tillage layer per tillage operation at any point of slope profile give

$$A = -0.2379RHC \qquad (13)$$

where $A$ = net erosion modulus of tillage layer per tillage operation at any point of slope profile, kg·m$^{2}$; $C$ = curvature at any point of slope profile, m·m$^{2}$.

As the curvatures on convex and concave position of slope profile are negative and positive respectively, equation (13) can theoretically give that the net erosion by tillage is produced on convexities of slope profile and the deposition by tillage appears on concavities of slope profile.

As the soil, tillage implement and tillage way everywhere in the Loess Plateau are basically coincident with which our experiment was performed in the typical area of Loess Plateau of China, equation (13) developed based on our tillage experiment can represent the model of tillage erosion in loess region of China. If the conditions of soil and tillage somewhere are not identical with our experimental conditions, coefficient of the model need to be modified with local conditions of soil and tillage.

Based on the established model of tillage erosion, we will further study intensities of tillage erosion, relative importance of tillage erosion in total erosion and relationships of tillage erosion with soil productivity, etc., and then propose practicable measures on reforming bad tillage way, controlling tillage erosion and preventing soil degeneration induced with tillage here.

## 4 Conclusions

Based on field experiment and theoretical analysis, a model of tillage erosion to directly calculate the modulus of net erosion by tillage at any point of slope profile. Results in the studied tillage operation manner are as follows:

1) Mean horizontal distance of soil displacement per tillage operation in slope aspect direction is linearly related to the tangent of slope gradient, and the empirical model is $D = -0.2379S + 0.0953$;

2) The net erosion modulus at any position of slope profile per tillage operation is affected by soil bulk density, tillage depth, coefficient determined with soil and tillage conditions, and topography curvature, the model of tillage erosion with these factors is $A = -0.2379RHC$.

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# 中国黄土地区耕作侵蚀模拟

王占礼, 邵明安
(中国科学院水利部水土保持研究所, 杨凌 712100)

**摘　要**: 耕作侵蚀是国际上新近开展的一个研究领域。为了对中国黄土地区的耕作侵蚀规律进行定量描述, 采用施放小立方块作为示踪材料进行耕作试验及测量来示踪和监测土壤运动, 并通过相关分析与理论推导, 对该地区的耕作侵蚀进行了模拟, 获得了能够直接计算出坡面剖面任何一点净侵蚀模数的耕作侵蚀模型, 结果表明, 在采用当地由动物牵引的传统犁在坡面上自下而上进行往返横坡等高向下翻土耕作方式下: 1) 一次耕作导致的耕层土壤朝坡向方向平均水平运动距离随坡度的变化表现为线性相关; 2) 一次耕作导致的坡面剖面任何位置耕层断面的净侵蚀模数, 受土壤容重、耕作深度、土壤与耕作条件决定的系数和地形曲率的影响。

**关键词**: 中国黄土地区; 耕作侵蚀; 模拟; 水平运动距离; 净侵蚀模数; 地形曲率