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INFLUENCES OF SLOPE GRADIENT ON SOIL EROSION *

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Abstract: The main factors influencing soil erosion include the net rain excess, the water depth, the velocity, the shear stress of overland flows, and the erosion-resisting capacity of soil. The laws of these factors varying with the slope gradient were investigated by using the kinematic wave theory. Furthermore, the critical slope gradient of erosion was driven. The analysis shows that the critical slope gradient of soil erosion is dependent on grain size, soil bulk density, surface roughness, runoff length, net rain excess, and the friction coefficient of soil, etc. The critical slope gradient has been estimated theoretically with its range between 41.5°~50°.

Key words: soil erosion; critical slope gradient; flow scouring capability; soil stability

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Introduction

Soil erosion can be classified into many types due to different eroding forces. Among them the surface runoff erosion is the commonest one. The slope gradient is one of the most important factors affecting the surface flow erosion. Under the same rainfall condition, the surface flow could be drastically different on different slopes, and thus the erosion quantity could also be enormously different. It is indispensable to study the relationship between the slope gradient and the surface soil erosion for soil erosion prediction and the soil-water conservancy planning. Many scholars have investigated this problem for decades. However, the results are greatly different since the complexity of the problem and the difference in viewpoint or object. Mainly they can be summarized in the following three respects:

1) Erosion law: In 1940, Zingg[1] analyzed the field data and got an empirical relationship between the soil erosion quantity and the slope gradient: $y = ax^b$ (where $a = 0.065$, and $b = 1.48$, x is the slope in degree and y is the soil erosion quantity). It shows that the soil erosion quantity is increasing with the slope gradient. TANG Li-qun and CHEN Guo-xiang (1997)[2] have established a soil erosion relationship in their small watershed runoff and sediment generation model. They also present a proportional relationship between soil erosion quantity and slope

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gradient. However, most of the field data and indoor artificial rain experiments show that this kind of relationship is kept valid only in a certain parameter range. If the slope gradient exceeds a threshold value, the relationship takes the inversely proportional form. For instance, Yaur and Klein (1973) [3] analyzed the data of soil erosion quantity on the ramps with the slope of 15°, 19° and 25° respectively and found that such inversely proportional relationship really appears. The fact infers the existence of the critical slope gradient in soil erosion.

2) Critical slope gradient: Renner (1936) [4] analyzed the field data of the Boise River watershed, Idaho in America, and found that the percentage of eroded area is different with the slope gradient. When the slope gradient exceeded 40.5°, the soil erosion quantity starts to decrease instead. CHEN Fa-yang (1985) [5] conducted a 9 groups of experiment by artificial rainfall in a $6m^2$ wooden box with variable slope degree and the soil was naked red clay formed in Quaternary period. Under the condition of fixed rainfall intensity, he got the critical slope gradient of soil erosion 25°. But Horton (1945) [6] obtained the critical slope gradient 57° in his analysis.

3) Quantitative relationships between soil erosion rate and slope gradient: Based on the data of interrill erosion for two kinds of soil on the slope from 3% to 50%, Singer and Blackard (1982) [7] assumed a polynomial relationship between soil erosion quantity and slope gradient. It was quadratic form $Dw = 0.22 + 9.37\sin Q - 8.43\sin^2 Q$ for silty clay, whereas it was cubic form $Dw = -0.10 + 7.66\sin Q + 59.49\sin^2 Q - 101.65\sin^3 Q$ for clay, where Dw is the interrill soil loss quantity, Q is the slope gradient. ZHANG Ke-li and Hosoyamada (1996) [8] studied the runoff and sediment generation on the ground with different slope gradient by indoor artificial rainfall. They also got a cubic formula $S = 1.211 - 21.98\sin Q + 119.6\sin^2 Q - 178.9\sin^3 Q$, where S is the soil loss quantity on the hillslope and Q is the slope gradient.

The differences in many researches indicate that there are a great many factors influencing the soil erosion process. Therefore, it is of great significance to analyze more carefully the influence of slope gradient for predicting soil erosion on a hillslope.

1 Hillslope Runoff Erosion and the Main Influencing Factors

Hillslope runoff erosion is such a process that sheet flow generated during rainfall scours the soil surface. Its motive power is the acting force of surface flow, while the erosion-resisting capacity is dependent on the stability of soil body. That is to say, the soil loss on the hillslope occurs when the scouring capability of surface runoff exceeds the erosion-resisting capacity. The whole process can be divided into three stages. Firstly, when the rainfall intensity is greater than the soil infiltration rate and the surface ponding capability, the rain excess flows down the hillslope under the action of gravity and thus forms the surface sheet flow. Then, when the scouring ability is greater than the erosion-resisting capacity of soil, the scour of soil particles are initiated. And finally, the scoured soil is transported downstream by overland flow. Therefore, the soil erosion rate indicates the ratio between the flow erosion ability (including the scouring ability and the transportation capability) and the erosion-resisting capacity of soil.

If we use τ_0, the flow bottom shear stress to represent the flow scour ability, and the incipient motion shear stress of soil particle τ_c to represent the erosion-resisting capacity, the surface soil erosion rate on hillslope can be expressed as[2]:

$$E_s = A(\tau_0 - \tau_c)v, \quad (1)$$

where A is a coefficient related to the compacted dry bulk density of soil γ_s, turbid water bulk density γ_m, and soil characteristic, etc. τ_0, τ_c are the flow shear stress and the sediment incipient shear stress on the hillslope surface respectively, v the velocity of the surface flow on the hillslope.

The foregoing expression shows that the surface flow and the erosion-resisting capacity of soil are the main factors affecting soil erosion. The flow shear stress and velocity on a slope with different gradient could be very different under the same rainfall condition, and the erosion-resisting capacity of soil is different as well. As a result, the soil loss rate is different correspondingly.

2 The Variation of Scouring Ability of Flow With the Slope Gradient

Because of the tiny depth of overland flow and the complicated boundary conditions, it is a tough task to describe the movement of this kind of flow appropriately. Usually the one-dimensional shallow water equation (Saint Venant equation) is used in modeling (Emmett, W. W., 1978) [9]

$$\frac{\partial h}{\partial t} + v\frac{\partial h}{\partial x} + h\frac{\partial v}{\partial t} = q, \quad (2)$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + g\frac{\partial h}{\partial x} + q^*\frac{v}{h} + g(S_f - S_0) = 0, \quad (3)$$

in which t is the time, x the distance, h and v represent the runoff depth and velocity, q^* means rain excess, S_0 the slope, S_f the energy slope, g the gravity acceleration.

When solving the above equations, the kinematic wave approximation is often adopted. Wolhiser and Liggett[10] have ever analyzed the one-dimensional unsteady overland flow. They find that when the kinematic wave number $K > 20(K = S_0L/h_0F_0^2)$, (in which S_0 is the slope, L is the runoff length, h_0 is the depth of the runoff in the distance L, F_0 is the Froude number) and $F_0 > 0.5$, the kinematic wave model can describe overland flow quite well. In most situations, this condition may be satisfied. Therefore we adopt the kinematic wave model, implying that the gravity component along the slope is equal to the resistance force, the above equation (3) could be simplified as

$$S_f = S_0 = \sin\theta. \quad (4)$$

Applying the kinematic wave theory, we have numerically simulated the process of overland flow formation of J. L. M. P. Lima's[11] indoor artificial rainfall experiment in 1992. (This experiment was done in a 0.5m^2 wooden box with length 1m, width 0.5m and 10% slope degree. The rainfall intensity is 135mm/hr and the soil is Limburg soil.) The comparison of computation and experiment in a fairly good agreement (Fig. 1) exhibits that the kinematic wave theory is suitable for describing overland flow.

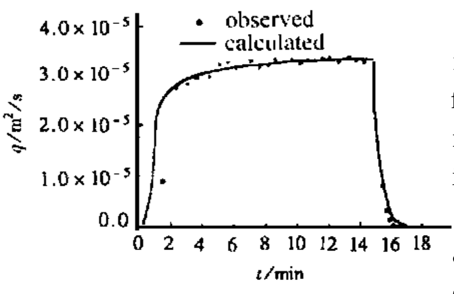


Fig. 1 Simulation result of overland flow by using the kinematic wave theory

2.1 The variation of the net rain excess with the

slope gradient

Let us consider the excess rainfall condition at first. The runoff yield is determined by the difference of rainfall intensity and soil infiltration rate. Suppose the rain is vertical, for a horizontal plane with the rainfall intensity I and the soil infiltration rate f, the rainfall excess turns out

$$q^{*} = I - f. \tag{5}$$

Nevertheless, for a hillslope there is an incline angle θ between the surface and the horizontal plane and $90°- \theta$ between the surface and the rainfall direction. The actual area receiving the precipitation varies with the slope gradient. It leads to the different rainfall amount on the same length of hillslope at different slope gradient. As showed in Fig. 2, if the area of the hillslope is AC for the surface with the slope of θ, the actual area receiving precipitation is reduced to AB ($= AC\cos\theta$). It means that the actual area receiving precipitation decreases with the slope.

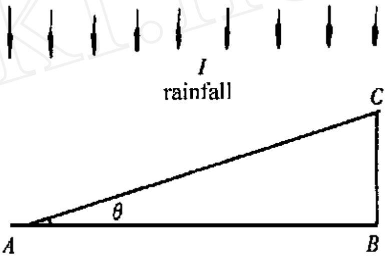


Fig. 2 The relationship of the actual receiving the precipitation and the slope θ

When the rain intensity (rainfall amount on unit area in unit time) corresponding to the horizontal plane is I, the actual rain intensity I_θ on the surface with the slope of θ is

$$I_\theta = I \cdot \cos\theta. \tag{6}$$

Assuming the infiltration rate does not vary with slope, the actual net rain amount on the slope becomes

$$q_* = I_\theta - f = I\cos\theta - f \tag{7}$$

meaning that the net rain amount on unit area in unit time decreases with the slope gradient.

2.2 The variation of runoff depth with the slope gradient

The variation rate of the discharge per unit width on the slope gradient is $\mathrm{d}q/\mathrm{d}x$, namely

$$\frac{\mathrm{d}q}{\mathrm{d}x} = q_* = I\cos\theta - f. \tag{8}$$

Therefore the discharge per unit width at the site L away from the top of the slope gradient under the condition of uniform rainfall is

$$q = \int_0^L \frac{\mathrm{d}q}{\mathrm{d}x}\mathrm{d}x = (I\cos\theta - f)L. \tag{9}$$

Suppose the water depth there is h. Using

$$q = vh. \tag{10}$$

We yield

$$vh = (I\cos\theta - f)L. \tag{11}$$

Although the motion of overland flows is so complicated that the law of resisting force is different from the usual open channel flow. In practical application, however, the concept and expression of resistance in an open channel, such as the Darcy-Weisbach formula, Chezy's formuls or Manning's formula can often be borrowed as an approximation for simplicity. Here we use the Manning's formula of uniform open channel flow, and the average velocity of the overland flows is

$$v = \frac{1}{n} h^{2/3} \sin^{0.5}\theta, \tag{12}$$

where n is Manning's roughness coefficient, θ the slope gradient of the surface. Then the depth of overland flow at length L looks like

$$h = \frac{[n(I\cos\theta - f)L]^{3/5}}{\sin^{0.3}\theta}. \tag{13}$$

While $\cos\theta$ is decreasing with the slope gradient θ, $\sin\theta$ is increasing, we can say from (13) that the roughness, the rainfall intensity, the runoff length and the infiltration rate of soil all would influence the overland flow depth. Generally, the flow depth increases with the surface roughness, the rainfall intensity and the runoff length, but decreases with the infiltration rate.

2.3 The variation of overland flow velocity with the slope gradient

We still use the Manning's resistance formula for uniform open channel flow, the average velocity of overland flows at length L is

$$v = \frac{1}{n} h^{2/3} \sin^{0.5}\theta.$$

Substituting Eq. (13) into the above expression, we derive

$$v = \frac{1}{n}[n(I\cos\theta - f)L]^{2/5} \sin^{0.3}\theta. \tag{14}$$

To simplify the analysis, Eq. (7) can be rewritten as

$$q_* = I\cos\theta - f = (I - f)\cos\theta - (1 - \cos\theta) f. \tag{15}$$

For ordinary slope gradient (less than 45°), $1 - \cos\theta$ is great less than $\cos\theta$. In the considered Horton's form of overland flow, the rainfall intensity is much greater than the soil infiltration rate, and the infiltration rate decreases with time until saturated, i.e., $f \to 0$. So the second term at the right hand side in the above formula could be ignored. So

$$q_* = I_\theta - f \approx (I - f)\cos\theta. \tag{16}$$

In this way Eq. (14) can be simplified to

$$v = \frac{1}{n}[n(I - f)L]^{2/5} \sin^{0.3}\theta \cos^{0.4}\theta. \tag{17}$$

This formula shows that the relation between the overland flow velocity and the slope gradient is more complex. And the roughness of the surface, the rainfall intensity and the runoff length all may influence the velocity. Generally, it will increase with the rainfall intensity and runoff length, while decrease with the surface roughness and the soil infiltration rate.

Differentiate the above formula with respect to θ, we have

$$\frac{dv}{d\theta} = \frac{1}{n}[n(I - f)L]^{2/5} \frac{0.3\cos^2\theta - 0.4\sin^2\theta}{\sin^{0.7}\theta \cos^{0.6}\theta}. \tag{18}$$

Let $dv/d\theta = 0$, we can conclude that the maximum value of overland flow appears at the slope is about 40.9°. The velocity increases with the slope in the scope of 0°～40.9°, and decreases with the slope θ greater than 40.9°. The relation between $v([n(I - f)L]^{2/5}/n)^{-1}$ and θ is showed in Fig. 3.

2.4 The variation of the scouring ability of overland flow with the slope gradient

Based on the kinematic wave approximation, the shear stress of overland flow τ_0 is

$$\tau_0 = \gamma h \sin\theta. \tag{19}$$

Considering (13), we have

$$\tau_0 = \gamma[n(I\cos\theta - f)L]^{3/5}\sin^{0.7}\theta. \tag{20}$$

In (20), $\cos\theta$ increases with θ, whereas $\sin\theta$ decreases with θ. Which shows the relation between the shear stress of overland flow and the hillslope is not monotonic. The runoff depth will decrease with the slope gradient while the energy slope will increase with the slope. The comprehensive consideration of the preceding two factors will determine the variation of the shear stress.

Simplifying (20) by using (17), we have

$$\tau_0 = \gamma[n(I - f)L]^{3/5}\sin^{0.7}\theta\cos^{0.6}\theta. \tag{21}$$

Differentiating (21) with respect to θ leads to

$$\frac{d\tau_0}{d\theta} = \gamma[n(I - f)L]^{3/5}\frac{0.7\cos^2\theta - 0.6\sin^2\theta}{\sin^{0.3}\theta\cos^{0.4}\theta}. \tag{22}$$

By virtue of $d\tau_0/d\theta = 0$, we find the maximum value of shear stress appearing at the slope about 47.2°. In other words, when the slope is in 0～47.2° the scouring ability of the flow increases with the slope, while the scouring ability decreases with the slope when the slope exceeds 47.2°. The relation of $\tau_0/[\gamma[n(I - f)L]^{3/5}]$ and θ is plotted in Fig. 4.

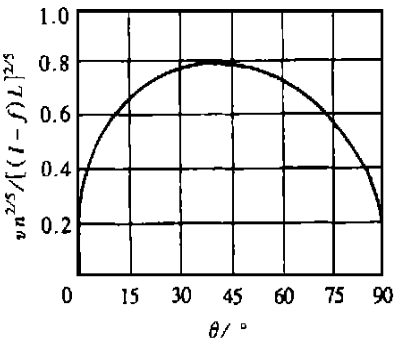


Fig. 3 The relationship of slope and the velocity fo overland flow

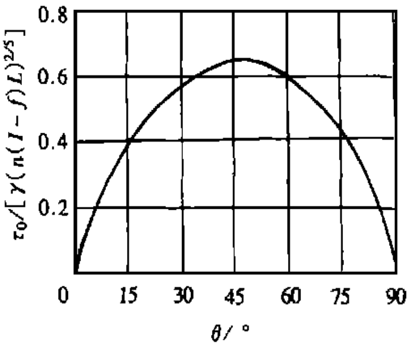


Fig. 4 The relationship of slope and the shear stress of overland flow

Furthermore, Eq. (21) shows that the actual scouring ability of overland flow relates also to the factors such as the surface roughness, the rainfall intensity, the runoff length and the soil infiltration rate, etc.

3 Variation of Erosion-Resisting Capacity of Soil With the Slope

The erosion-resisting capacity of soil is mainly dependent on the factors such as characteristics of soil, the plant coverage and the surface slope gradient, etc. Actually, the soil characteristics and plant coverage are often very complicated. Here we mainly focus on the effect of the slope gradient on the erosion-resisting capacity of soil. To simplify the problem, we use the natural binding force of soil, τ_1 to represent the erosion-resisting effect of soil, and use the adhesion force τ_2 to represent the erosion-resisting force of vegetation. Generally we have:

$$\tau_1 = f(\text{soil types, gradation, chemical components in soil, } \cdots), \tag{23}$$

$$\tau_2 = f(\text{plant coverage percentage, vegetation types, } \cdots). \tag{24}$$

The gravity of soil is also an important factor on soil stability. Suppose the representative grain size is d, the friction coefficient is N_0. When on horizontal ground, the friction resistance caused by soil particle gravity (within the range of one particle diameter) is

$$\tau_3 = N_0(\gamma_s - \gamma) d, \tag{25}$$

where γ_s, γ represent soil dry bulk density and water bulk density respectively.

On the surface with the slope of θ, the particle gravity could be decomposed to two forces with different effect on soil particle. The component perpendicular to the slope has the effect leading to stability, while the other component parallel to the slope has the effect leading to instability. The friction resistance caused by the gravity component perpendicular to the surface is

$$\tau_3 = N_0(\gamma_s - \gamma) d\cos\theta, \tag{26}$$

the force parallel to the surface is

$$F = (\gamma_s - \gamma) d\cos\theta. \tag{27}$$

Combining all factors together gives rise to the scour resisting force as follows:

$$\tau_c = \tau_1 + \tau_2 + (\gamma_s - \gamma) d(N_0\cos\theta - \sin\theta), \tag{28}$$

which shows that the erosion-resisting capacity decreases with the slope gradient θ, that is, the soil stability decreases with θ. Eq. (28) also shows that the stability of soil on the slope is related to soil characteristics, plant coverage and grain size, etc.

4 The Critical Slope Gradient of Soil Erosion

Most artificial rainfall experiments and field observations show that the soil erosion is proportional to θ within certain slope θ. While the soil erosion quantity decreases with θ as θ exceeds a certain value. Since the complexity of influencing factors and the difference in the method adopted by different scholars, the critical slope gradients were greatly different. Renner (1936) [4] obtained the critical value of 40.5°. CHEN Fa-yang (1985) [5] got it of 25°. Horton (1945) [6] analyzed this problem theoretically in 1945. Without considering the soil infiltration, he analyzed the runoff depth and slope gradient relation and derived out the relation between flow shear stress and the slope gradient θ based on the kinematic wave approximation. He assumed that critical slope gradient was 57°. CAO Wen-hong (1993) [12] further considered the effects of surface roughness, soil particle size, rainfall, infiltration and runoff length on the flow shear stress and found that the critical slope gradient was not a constant due to the influence of these factors and close to 41°. Although these analyses described the problem quite carefully, but they all ignored the erosion-resisting force and transport capacity of flow. As a matter of fact, we know from the above analysis, that besides the flow scouring ability varying with the slope gradient, the erosion-resisting capacity of soil also would vary with the slope gradient, and the velocity the flow transport the sediment would vary with the slope gradient as well. Therefore the three aspects of factors should be taken into account entirely in the analysis of soil erosion.

According to the above analyses, the overland flow shear stress τ_0, the erosion-resisting capacity τ_c, and the flow velocity v are represented as

$$\tau_0 = \gamma[n(I - f)L]^{3/5}\sin^{0.7}\theta\cos^{0.6}\theta,$$

$$\tau_c = \tau_1 + \tau_2 + (\gamma_s - \gamma) d(N_0\cos\theta - \sin\theta),$$

$$v = \frac{1}{n}[n(I - f)L]^{2/5}\sin^{0.3}\theta\cos^{0.4}\theta$$

respectively.

Analysis Ⅰ:

Consider merely the effect of overland flow shear stress and the erosion resisting capacity of soil. Then we have

$$E_s \propto \tau_0 - \tau_c$$

and

$$\tau_0 - \tau_c = \gamma[n(I - f)L]^{3/5}\sin^{0.7}\theta\cos^{0.6}\theta - \tau_1 - \tau_2 - (\gamma_s - \gamma)d(N_0\cos\theta - \sin\theta). \quad (29)$$

Differentiating the above equation with θ, by $d(\tau_0 - \tau_c)/d\theta = 0$, we may obtain the following relation about critical slope gradient θ_m:

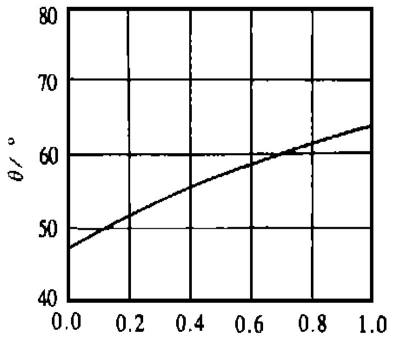
$$\frac{0.6\sin^2\theta_m - 0.7\cos^2\theta_m}{(\sin^{0.3}\theta_m - \cos^{0.4}\theta_m)(N_0\sin\theta_m + \cos\theta_m)} = \frac{\gamma_s - \gamma}{\gamma}\frac{d}{[n(I - f)L]^{3/5}}. \quad (30)$$

Thus

$$\theta_m = F\left(\frac{\gamma_s - \gamma}{\gamma}, d, n, I - f, L, N_0\right). \quad (31)$$

It is obvious that the critical slope gradient is dependent on many factors such as the grain size, soil bulk density, surface roughness, runoff length, net rain excess, and the friction coefficient of soil.

If the friction coefficient N_0 takes the value of 0.047, we could get the relation between the critical slope gradient θ_m and the synthesis coefficient (Fig.5(a)). We could see on the hillslope of same soil characteristic, the larger the surface roughness and the longer the runoff length and the greater the net rain excess, the smaller the critical slope gradient.



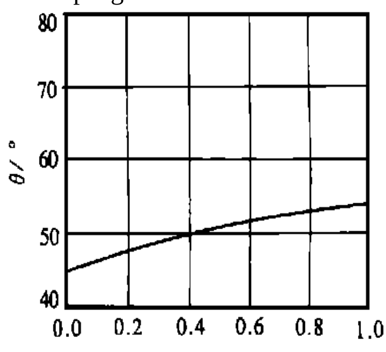


Fig.5 Variation of the critical slope gradient (θ_m) with $\frac{\gamma_s - \gamma}{\gamma}\frac{d}{[n(I - f)L]^{3/5}}$

Analysis Ⅱ:

Consider the three factors, the scour ability of flow τ_0, the erosion-resisting capacity of soil τ_c and the velocity the runoff transporting the sediment v, simultaneously, and ignore the binding force between grains τ_1 and the concretion force of plant coverage τ_2. Substitute τ_0, τ_c, v into (1). With some manepulation the soil erosion rate on the hillslope takes the form

$$E_s = A[\gamma(I - f)L\sin\theta\cos\theta - \frac{d}{n}[n(I - f)L]^{2/5}(\gamma_s - \gamma)(N_0\sin^{0.3}\theta\cos^{1.4}\theta - \sin^{1.3}\theta\cos^{0.4}\theta)]. \quad (32)$$

The above formula shows that the factors influencing soil erosion are very complicated. The slope gradient is just one of the main factors. This is the essential reason responsible for the great difference in the critical slope gradient by scientists.

Differentiate (32) with respect to θ. Following the relation $\mathrm{d}E_s/\mathrm{d}\theta = 0$, we obtain the relation with which the critical slope gradient θ_m satisfies

$$\frac{\sin^{0.7}\theta_m\cos^{0.6}\theta_m(\cos^2\theta_m - \sin^2\theta_m)}{N_0\cos\theta_m(0.3\cos^2\theta_m - 1.4\sin^2\theta_m) - \sin\theta_m(1.3\cos^2\theta_m - 0.4\sin^2\theta_m)} = \frac{\gamma_s - \gamma}{\gamma}\frac{d}{[n(I - f)L]^{3/5}}. \quad (33)$$

We also have

$$\theta_m = F\left(\frac{\gamma_s - \gamma}{\gamma}, d, n, I - f, L, N_0\right).$$

That is, the critical slope gradient of soil erosion is a variable that varies with the grain size, the soil bulk density, the surface roughness, the runoff length, the net rain excess, and the soil friction coefficient, etc.

Taking the friction coefficient $N_0 = 0.047$, we obtain the relation between the critical slope gradient θ_m and the synthesis coefficient $\frac{\gamma_s - \gamma}{\gamma}\frac{d}{[n(I - f)L]^{3/5}}$, as in Fig. 5(b). It also shows the critical slope gradient decreases with the surface roughness, the runoff length, and the net rainfall excess.

In the synthesis coefficient $\frac{\gamma_s - \gamma}{\gamma}\frac{d}{[n(I - f)L]^{3/5}}$, the unit of roughness n is $s/m^{1/3}$, the unit of net rainfall excess is m/s. Actually, the value of surface roughness is about 0.02～0.06, the net rainfall excess is about 20mm～100mm/h, the surface length is about 20m～1 000m. They determine the value of $\frac{\gamma_s - \gamma}{\gamma}\frac{d}{[n(I - f)L]^{3/5}}$ which generally is quite small, about 0.03～0.3. Therefore, we conclude that the critical slope gradient of the soil erosion should be generally in the range of 41.5°～50°.

5 Conclusions

1) The shear stress of overland flow, the erosion-resisting capacity of soil and the overland flow velocity are the three main respects determining soil erosion on the slope surface. However, the influencing factors should include slope gradient, rainfall intensity, infiltration rate, soil characteristics, grain sizes, surface roughness, plant coverage and runoff length.

2) The slope is an important factor influencing the overland flow generation and soil erosion. It has significant effect on the net rain excess, the overland flow depth, the flow velocity and the shear stress. Generally speaking, the net rainfall excess decreases with the slope, the flow velocity first increases with the slope, and reaches the maximum value when slope increases to 40.9°, then they decrease with the slope. The same situation occurs to the flow shear stress and

the only difference is it reaches the maximum value at the slope gradient of 47.2°.

3) The erosion-resisting capacity of soil generally decreases with the slope gradient.

4) The soil erosion on the slope surface does have a critical slope gradient dependent on grain sizes, soil bulk density, surface roughness, runoff length, net rain excess and soil friction coefficient. However, it is generally between the range of 41.5°~50°. For the surface with the same soil characteristics, the rougher the surface or the longer the runoff length or the greater the net rain excess, the smaller the critical slope gradient.

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