

CALCULATION MODEL AND EXPERIMENTAL STUDY ON SEDIMENT EROSION OF SLOPE UNDER EXTERNAL-SOIL SPRAY SEEDING

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ABSTRACT

Due to the current lack of theoretical study on rain erosion of the slope under external-soil spray seeding, the calculation model applicable to slope sediment erosion under external-soil spray seeding was derived from hydraulics theory and energy method. Designed slope scouring test on indoor model, conducted 3 separate scouring tests under 3 different slope rates (1:0.75, 1:1, 1:1.25) and 3 different rainfall intensities (120, 150, 180mm/h). The rationality of the calculation model was verified by the experimental data. Meanwhile, also analysed the developing regularities of slope erosion and relationship among sediment erosion, rainfall duration, rainfall intensity and slope rate. The results show that the relative error between the theoretical value and measured data is within 18%, and the calculation model can accurately predict the sediment erosion of the slope under external-soil spray seeding to some extent; the slope under external-soil spray seeding is lack of erosion resistant ability, and the slope erosion is mainly rill erosion and layered surface erosion; the amount of sediment erosion is positively correlated with rainfall intensity and slope rate. The relationship between growth rate and rainfall duration basically remained the same during the first 20 minutes, and then gradually decreased.

KEYWORDS

External-soil spray seeding, Slope erosion, Energy method. Model test

INTRODUCTION

In the 1980s, Japan was the first country to carry out study on external-soil spray seeding technology [1], which China has introduced in the early 1990s and successively carried out experimental study in south China and loess plateau [2]. Since the 20th century, external-soil spray seeding technology, as the most important ecological protection technology, has been widely applied nationwide [3]. This technology is able to spray soil mixture evenly into the bare rock or soil slope through the mixing and spraying pump for external soil, advanced processing and meshing on the slope is generally required. The soil mixture consists of base material soil, fertilizer, water retaining agent, pH regulator, water, and various selected plant seeds etc. allocated by reasonable proportions, which will and finally protect the environment and beautify the slope. It has the

advantages of sound slope protection effect, wide application range, economic, beautiful and strong sustainability etc. [4].

In rainy cities, due to the sudden torrential rains, the external-soil spray seeding is susceptible to heavy rainfall after its completion. Surface runoff on the slope can take away a lot of sediment, which will lead to serious sediment erosion [5]. As for external-soil spray seeding on the highway subgrade slope, Wang Yimin et al. [6] studied the resistant ability of the slope under external-soil spray seeding for rain scouring at the initial stage after construction and vegetation growth. The result shows that at early spraying, the slope is lack of ability to resist rain scouring, and protective measures must be taken to protect the plant seeds. In practical engineering application, put a layer of non-woven cloth on the slope after construction is the normal practice adopted to prevent or reduce the sediment erosion caused by rainfall on the slope. However, in case of heavy rainfall, sediment erosion phenomenon is still serious, even with the help of protective measures. As shown in Figure 1, a slope for external-soil spray seeding with non-woven fabric was built in the west campus of the college. After heavy rain, a lot of gullies have occurred on the slope, mesh steel material was exposed, large sediment erosion was occurred and the plant is difficult to completely cover the slope in the later stage, because a large number of plant seeds were taken away by runoff on the slope. For abovementioned reasons, re-construction is needed and may lead to serious economic losses.



Fig. 1 - Sediment erosion

Therefore, considering the larger sediment erosion resulted from rain scouring on the slope under external-soil spray seeding after construction; it is necessary to conduct theoretical calculation on its sediment erosion. It would be of theoretical guidance to practical engineering to derive calculation model through theories, verify the accuracy of model by designing test and accurately grasp the developing regularities of sediment generated from external-soil spray seeding under multiple conditions.

Calculation Model for Sediment Erosion

Hydraulic Analysis of Water Flow on the Slope

Simulated water flow on the slope is as shown in Figure 2; flow rate at L point of the slope could be derived from Manning Formula, see Equation (1).

$$v_L = \frac{1}{n} h_\alpha^{\frac{2}{3}} \tan^{0.5} \theta \quad (1)$$

In the above formula, h_α refers to confluent depth, n refers to roughness ratio and θ refers to the angle between the slope and horizontal surface.

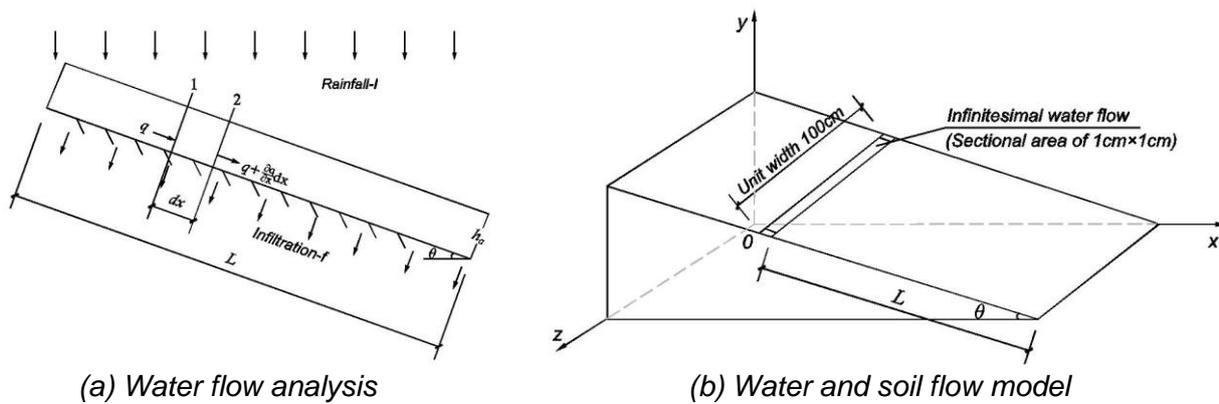


Fig. 2 - Analysis of water flow on the slope

The relationship between micro-segment flow and increased runoff (determined by rainfall intensity and infiltration rate) can be established by reference to the infinitesimal water flow relationship between section 1 and section 2. Refer to the single-width flow formula derived by Horton [7] in calculating the critical slope under soil erosion at the slope length of L and make some modifications, take α as the angle between the rainfall direction and the vertical direction of the slope. When the rainfall direction is vertical, the value is equal to the angle between the slope and the horizontal plane. Please refer to Equation (2) for the specific formula.

$$q = \int_0^L \frac{\partial q}{\partial x} dx = \int_0^L (I - f) dx \cos \alpha = (I - f)L \cos \alpha \quad (2)$$

According to the hydraulics theory, the single-width flow can also be expressed as the product of flow velocity and confluent water depth, and it can be combined into the Equation (2) as follows:

$$q = v_L h_\alpha = \frac{1}{n} h_\alpha^{\frac{5}{3}} \tan^{0.5} \theta = (I - f)L \cos \alpha \quad (3)$$

Finally, the confluent water depth could be derived from the Equation (3), see Equation (4).

$$h_\alpha = \left[\frac{n(I - f)L \cos \alpha}{\tan^{0.5} \theta} \right]^{0.6} \quad (4)$$

With reference to the “Designing Specification on Highway Drainage” [8], catchment time of the slope is:

$$t = 1.445 \left(\frac{nL}{\sqrt{\tan \theta}} \right)^{0.467} \quad (5)$$

In the above formula, I refers to the standard rainfall intensity, f refers to the infiltration rate, and both units are m/min.

Derivation of the Energy Method Formula

At present, there are many methods for calculating the amount of sediment erosion on the slope, such as establishing empirical models based on a large number of measured data [9], establishing mathematical equations based on hydraulic theory [10], and using neural networks to predict the amount of sediment erosion [11,12] etc. However, there are certain problems in the above methods, such as excessive influence factors of sediment erosion on the slope [13]; difficult to clarify the relationship between various factors; over complicated mathematical formula and

insufficient accuracy of the results etc. Li Zhigang et al [14] proposed to calculate the amount of sediment erosion by using the energy conservation law for the first time, and successfully applied this method to calculate the amount of sediment erosion in geotechnical structures. Based on the hydraulics theory, the energy method is to calculate the sediment erosion on the slope by the energy conservation law, which is not only simple in terms of the mathematical formula, but can also reflect the relationship among influence factors to some extent.

Energy distribution and transformation during slope erosion obey the energy conservation and conversion law [15]. According to the variation of water flow in soil and energy during rain scouring and erosion, the energy balance equation of slope soil under scouring is established as follows:

$$E_0 + E_1 = E_2 + E_3 \quad (6)$$

In the formula, E_0 refers to the potential energy of water flow in soil, E_1 refers to the initial kinetic energy of water flow in soil, E_2 refers to the frictional energy dissipation, and E_3 refers to the kinetic energy of water flow in soil.

During the movement of water flow in soil, the friction is the product of the positive pressure of the moving material on the slope and the friction coefficient. In the formula, the friction coefficient is expressed by the roughness rate n . At the same time, it is assumed that the variation of mass along the path of water flow in soil is linear, and the frictional energy dissipation E_2 can be obtained by the frictional force integration along the movement distance. See Equation (7).

$$E_2 = \int_0^L ng(m_1 + \frac{\Delta m}{L}x)\cos\theta = ngL(m_1 + \frac{\Delta m}{2})\cos\theta \quad (7)$$

The external-soil spray seeding technology is widely used for the cutting slope. Basically, there is no catchment at the top of the slope. The initial kinetic energy of water flow in soil E_1 is equal to 0. The kinetic energy of water flow in soil can be derived by taking the velocity v_L at the foot of the slope, and energy balance equation for the simulated slope is obtained:

$$m_1gL\sin\theta + \frac{1}{2}m_1v_1^2 = ngL(m_1 + \frac{1}{2}\Delta m)\cos\theta + \frac{1}{2}(m_1 + \Delta m)v_2^2 \quad (8)$$

$$\Delta m = m_1 \frac{2gL\sin\theta - 2ngL\cos\theta - v_2^2}{ngL\cos\theta + v_2^2} \quad (9)$$

Δm is the variation of water flow in soil, including the increased sediment m_2 and the increased rainwater ΔQ , i.e.

$$\Delta m = m_2 + \Delta Q \Rightarrow m_2 = \Delta m - qt \quad (10)$$

By substituting Equations (1), (4), and (5) into Equations (9) and (10), a function of the sediment erosion m_2 on the slope could be derived:

$$m_2 = F(I, f, L, n, \theta, \alpha) \quad (11)$$

The catchment on the slope is equal to the total flow at the foot of the slope, i.e. $M = \rho qtB = \rho v_L h_\alpha tB$, where B is the slope width, ρ is the water density, and t is the catchment time of the slope.

The initial mass of the infinitesimal water flow on a single width area is:

$$m_1 = \rho \times 10^{-4} = 0.1\text{kg} \quad (12)$$

The total amount of sediment erosion on the slope is

$$\Delta M = \frac{m_2}{m_1} M \quad (13)$$

Scouring Test on Indoor Slope Model

Test Device

The scouring test on indoor slope model was carried out by using a self-made test vehicle. It is mainly composed of a frame, a guide frame, a model frame, a support system and a rainfall system, as shown in Figure 3(a).

(1) Frame

There are 4 universal wheels with brakes at the bottom of the frame. The frame is made of unequal angle iron, with a height of 50cm, a base size of 1.5*0.6m and an angle iron specification of 70*50*8mm. Slanting rod of the frame is connected to the frame base by a hinge, and four holes are reserved on the slanting rod for connecting the model frame.

(2) Guide Frame

The guide frame is composed of equilateral angle iron (with a specification of 30*30*3mm and a length of 30cm) and steel bar (with a diameter of 18mm and a length of 35cm); the two form a triangular support with the frame base. The top surface of the triangular support has a slope of 15°; laying a wooden board with a size of 40*90*8mm on the support and fixing it with the triangular structure by iron wire. It is a trenched wooden board, as shown in Figure 3(b), with a position left for the hinge at the upper end of the wooden board, which enables the wooden board to be embedded under the model frame, so as to ensure that the groove can be completely used for collecting rainwater. Side plates with a height of 8cm are arranged on both sides of the wooden board and the water outlet; a plastic film is laid in the guide groove to prevent rainwater flow out from the assembling gap of the wooden board and makes it easy to collect the sediment brought by scouring.

(3) Model Box

The model box is made of 2cm thick wood, with an inner frame size of 800*1200*1200mm. Put nails on the bottom plate, hang the thin wire netting, lay fine stone concrete (2cm thick), and finally roll the slope with the roller. Hang the thin wire netting could prevent the concrete from cracking and ensure a complete slope.

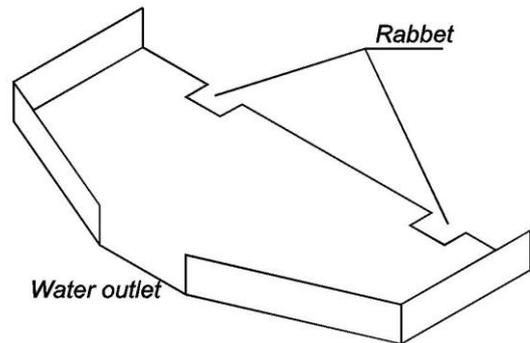
(4) Support System and Rainfall System

The support system is mainly composed of a support rod and a support baffle, which changes the slope rate by adjusting the supporting points. Learned from the designing experience of rainfall simulators in existing studies [16-19], the rainfall system designed in this test consists of a wooden bracket, a wire mesh frame, a spray device, and a voltage stabilizing and flow control device. The wire mesh is hold up on the wooden support and parallel to the slope. The spray device is composed of 10 copper nozzles and rubber tube, with a size of 400*800mm, as shown in Figure 3(c), which is fixed on the iron grid by the self-locking nylon cable tie. The copper nozzle is adjustable mist sprayer, with a specification of the following: diameter of the nozzle orifice is 1.2cm, operating pressure (0.2-0.5Mpa), spraying diameter (0-60 cm), spraying flow rate (0-140L/h); inner diameter and outer diameter of the rubber tube is 8mm and 12mm respectively. The nozzle is 50cm above the ground, with its orifice vertical to the slope. Modify the spraying diameter of the nozzle and its position before the test, so as to ensure uniform rainfall distribution in the model box;

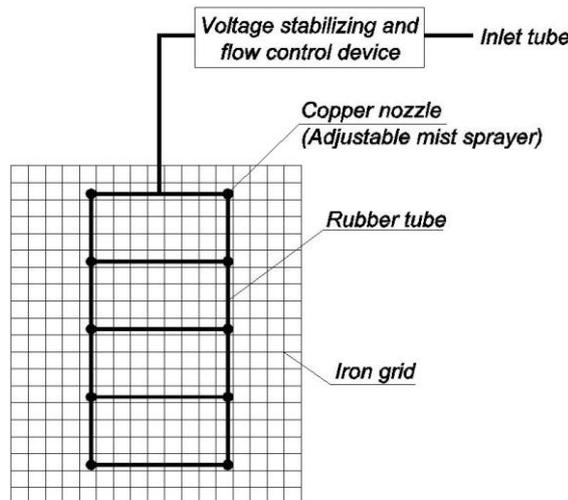
meanwhile, to prevent rainfall distribution outside the model box, no wind is allowed in the room. Based on abovementioned prerequisites, the uniformity of rainfall distribution is determined as 86.5%. The maximum rainfall intensity of the rainfall simulator is 800mm/h; kinetic energy of the rainfall is $33.45 \text{ J} \cdot \text{m}^{-2} \cdot \text{mm}^{-1}$, $41.79 \text{ J} \cdot \text{m}^{-2} \cdot \text{mm}^{-1}$ and $50.13 \text{ J} \cdot \text{m}^{-2} \cdot \text{mm}^{-1}$ under a rainfall intensity of 120mm/h, 150mm/h and 180mm/h respectively. Without changing the opening status of the nozzle and valve, the rainfall intensity of the sprayer is stable with the help of voltage stabilizing and flow control device.



(a) Model test vehicle



(b) Guide groove



(c) Rainfall system
Fig. 3 - Test device

Test Plan Design

(1) Rainfall Intensity

Rainfall intensity of the test is determined and derived in accordance with the storm intensity formula and specifications [20]. The selected area of the storm intensity formula is Shapingba, where the campus is located, see Equation (14).

$$q = \frac{1132(1 + 0.958 \lg P)}{(t + 5.408)^{0.595}} \quad (L / s \square m^2) \quad (14)$$

Where P is the recurrence period of the design, the unit is year (a);

q is the intensity of torrential rain, the unit is $L/s \cdot hm^2$;

t is the duration of the rain, the unit is min.

According to the requirements of the specification [20], take $P=3$, $t=5min$. It can be calculated by taking the formula (14) that $q = 409.26L/s \cdot hm^2$, based on the conversion formula, the rainfall intensity under standard unit is:

$$I = \frac{q}{166.67} \times 60 = 147mm/h \quad (15)$$

The designed rainfall simulator controls the rainfall intensity by flow rate, the calculated rainfall intensity needs to be converted for the convenience of the test. In the preparation stage, the rainfall is ensured to be distributed completely on the designed slope as far as possible, thus the minor rainfall outside the slope can be ignored. Therefore, the derived flow rate is $Q=2.3568$ L/min, which is based on a slope area of $0.96m^2$ and a rainfall intensity of $I = 147mm/h$. In order to control the test easier, take $Q=2.4$ L/min and correspondent rainfall intensity $I = 150mm/h$. Meanwhile, considered a fluctuation of 20% to simulate situation under heavy rain and torrential rain, namely $I = 120mm/h$ (rainfall area is $0.96 m^2$, correspondent flow rate $Q=1.9$ L/min) and $I = 180mm/h$ (rainfall area is $0.96 m^2$, correspondent flow rate $Q=2.9$ L/min).

(2) Experiment Material

The slope material for external-soil spray seeding is mainly composed of organic nutrient soil. Considering that the calculation model is mainly used to calculate sediment erosion after the slope engineering, the situation after vegetation growth is not considered in this calculation model. Therefore, various additives used to assist plant growth in the external-soil spray seeding are not considered in the test, and the test soil is only organic nutrient soil.

(3) Model Making

Measuring the water content of the organic nutrient soil in advance, adding correspondent proportion of water according to the water content required by the test, putting together the mixture with a soil mixing tool, and then infiltrated for 24 hours. The soil is paved in the model box by layered compaction method, each layer with a thickness of 1cm. After compacting one layer, scrape off the excess part with a scraper, then shave the surface of the soil with a geo-knife and compact it, 5 layers in total.

(4) Artificial Rainfall

The artificial rainfall adopts nozzle for simulated water spray, reasonably control the nozzle spacing and angle to ensure uniform rainfall. A bucket was placed at the water outlet of the guide frame to collect the mixture of rainwater and sediment brought by the scouring on the slope surface. The designed rainfall duration is 60 minutes, and the data was collected every 10 minutes, 6 groups of data in total.

(5) Test Group

In order to consider the influence of different rainfall intensity and slope rate on the sediment erosion under external-soil spray seeding, three slope rates were selected for comparison, namely 1:0.75, 1:1, 1:1.25. Based on the standard rainfall intensity derived from the intensity of torrential rain, with a fluctuation of 20%. The conditions of heavy rain and torrential rain were simulated respectively. The test group is as shown in Table 1.

Tab. 1- Test group

| Working Condition | Slope Rate | Rainfall Intensity/ (mm/h) |
|-------------------|------------|--------------------------------|
| 1 | 1:0.75 | 120 |
| 2 | 1:0.75 | 150 |
| 3 | 1:0.75 | 180 |
| 4 | 1:1 | 120 |
| 5 | 1:1 | 150 |
| 6 | 1:1 | 180 |
| 7 | 1:1.25 | 120 |
| 8 | 1:1.25 | 150 |
| 9 | 1:1.25 | 180 |

TEST RESULTS

Slope Erosion

Under the action of rainfall erosion, the erosion process of slope generally follows the sequence of raindrop erosion - layered surface erosion - rill erosion [21, 22]. Taking the experimental group with a slope rate of 1:1 and a rainfall intensity of 150mm/h for erosion effect analysis. From the beginning of rainfall, record the status of slope erosion by every 10 minutes. The rainfall lasted for 60 minutes and was recorded for 6 times. See Figure 4.

In the early stage of rainfall, the soil is in the state of natural moisture, with strong water absorption capacity. The initial process of slope erosion occurs while most rainwater infiltrates into the soil and erodes the slope. The impact of raindrops on the slope causes the surface soil to become loose, and the floating soil begins to roll along the slope with raindrops as they hit. As the soil gradually became saturated and rainfall intensity became greater than the infiltration rate, the slope surface began to fall and formulate a fluid or a shallow flow along the slope. At this moment, the kinetic energy of water flow is small, and the runoff is also scattered and broad, which can only take away suspended or condensed fine soil particles and dissolved substances on the surface, and result in a layered surface erosion mainly eroded by a thin layer of water flow. Due to the small pits formed by raindrop erosion in the early stage, and the micro-topographic fluctuation on the slope, the sheet flood produces differentiated erosion on the slope, and then gradually develops into the thin water flow with obvious flow path. The hydraulic drop appears under the action of thin water flow, indicating that the rill erosion begins to form, which is an important cut-off point of erosion mode variation.

When the rainfall lasted for 10min, visible ridges were formed in the lower right part of the slope, with a depth of 0.2cm-0.8cm. The upper left part of the slope was less eroded and the slope is smooth. Other areas of the slope have different degree of layered surface erosion. When the rainfall lasted for 20min, the ridge continued to develop, and the depth reached about 1cm. At the same time, a new rill began to form in the lower left part of the slope. The layered surface erosion still occurs in the upper left area of the slope, Surface erosion on remaining parts of the slope was deepened, and shows obvious scale-like shape. When the rainfall lasted for 30 minutes, the rill in the lower right region began to develop upward, and the depth gradually deepened. New rill was formed in the middle and lower regions, and the rest of the slope was in the state of layered surface erosion, with more obvious scale-like shape. After 40 minutes of rainfall, the rill began to widen and the deepening trend began to slow down. At the same time, new rill began to branch from the existing rill and developed into various directions, among which the vertical rill is the

fastest developed one. A pit was formulated in the left and right area, which is mainly due to a puddle was gradually formed by accumulated rainfall during its horizontal development process on the basis of the rill, with sediment at the bottom of the pit taking away by the water flow, a visible pit was gradually formed. When the rainfall lasted for 50min and 60min, the existing rill continued to develop, the surface erosion became more obvious, and the slope erosion began to stabilize.

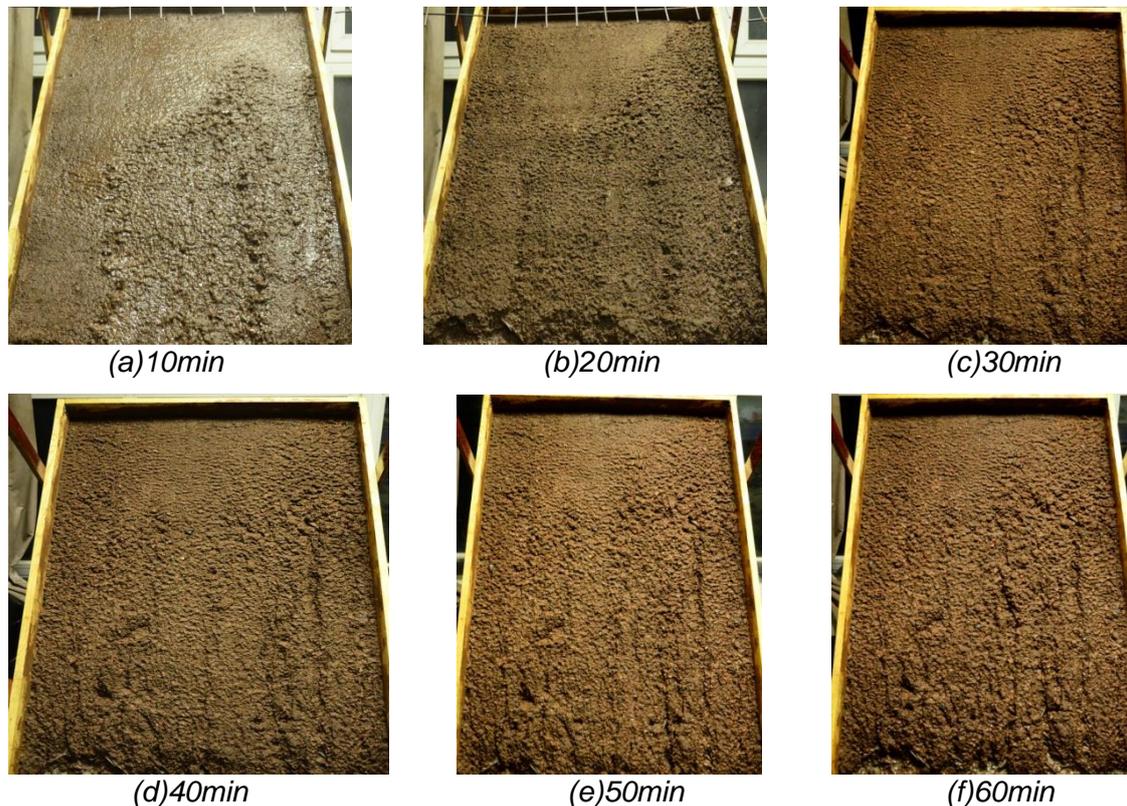


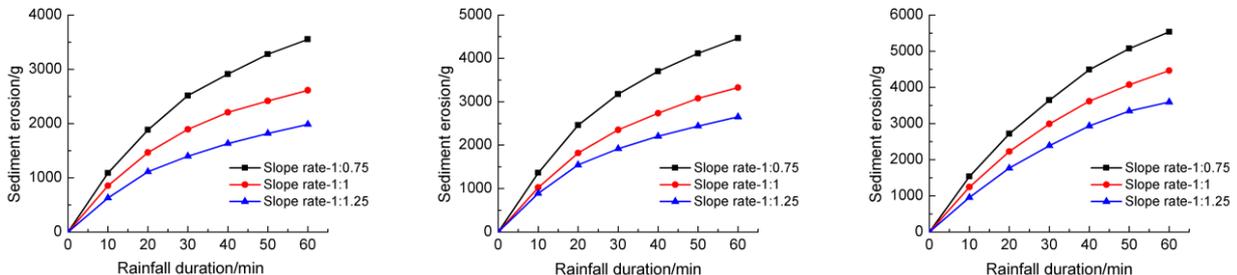
Fig. 4 - Slope erosion

Analysis of Sediment Erosion

Keep each group of bucket static for 24 hours, carefully separate mud and rain, ensure no sediment outflow, then use iron plate to collect the remained mixture of sediment and water. Put it into the drum wind drying oven with a temperature of 110°C , measure the weight of dried soil after 24 hours and record the sediment concentration in each group. Plot the relationship curve between accumulated sediment erosion and rainfall duration, as shown in figure 5.

It can be found from the three sets of curves that sediment erosion increases with the increase of rainfall duration under each working condition. For the working conditions under rainfall intensity of 120mm/h and 150mm/h , the increasing trend basically increases linearly before the rainfall duration of 20min, and then slows down after 20min. However, in the case of rainfall intensity of 180mm/h , the sediment growth rate began to slow down after the rainfall lasted for 30min, the decelerated increase rate appears later at the slope rate of 1:0.75, and began to decelerate after the rainfall lasted for 40min. This regularity indicates that under higher rainfall intensity and steeper slope, the longer the linear increase of sediment erosion is maintained, the more serious the slope erosion damage is. In the late rainfall duration, the growth rate of sediment erosion seems slowdown, which reflects that rill development and surface erosion tends to be stable in the late stage of the actual slope erosion. There is no sudden increase of large rill, with sediment on existing rills gradually taken away under the erosion of runoff on surface, gully

gradually appears. The sediment erosion during this process was less than that in the initial stage and its growth rate was relatively stable.



(a) Rainfall Intensity-120mm/h (b) Rainfall Intensity-150mm/h (c) Rainfall Intensity-180mm/h
 Fig. 5 - Curve of sediment erosion and rainfall duration

In order to analyse the influence of rainfall intensity and slope rate on sediment erosion in a comprehensive manner, taking rainfall intensity and slope rate as the horizontal coordinate, and the sediment erosion under a rainfall duration of 60 minutes as the vertical coordinate to draw curves, as shown in Figure 6 and Figure 7.

From the relationship curve of sediment erosion and rainfall intensity, the sediment erosion increases with the increase of rainfall intensity. The curve tends to be concave under a slope rate of 1:1 and 1:1.25, which indicates that under the rainfall intensity of 120-150mm/h, the rainfall intensity and sediment erosion increase slowly. Sediment erosion increases faster under the rainfall intensity of 150-180mm/h; under the slope rate of 1:0.75, the increase rate of sediment erosion is relatively consistent, and the curve is basically linear.

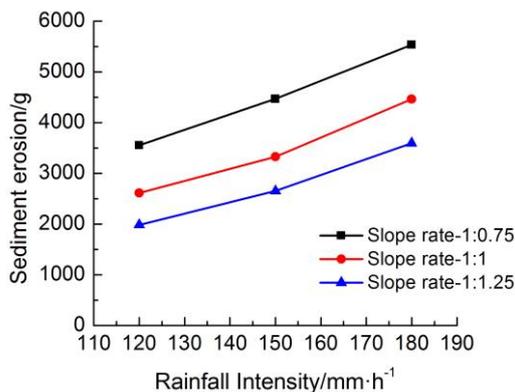


Fig. 6 - Relationship between sediment erosion and rainfall intensity

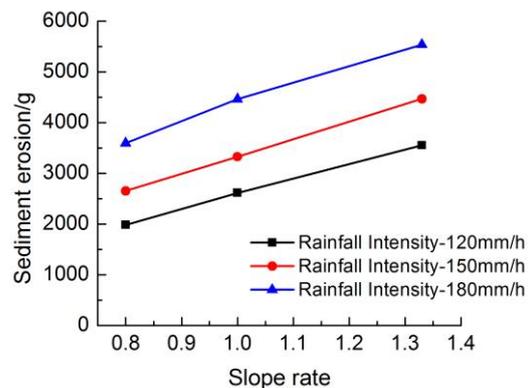


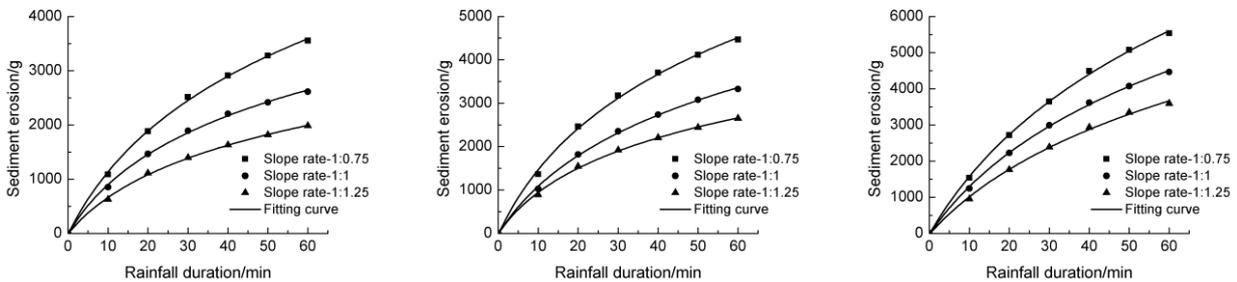
Fig. 7 - Relationship between sediment erosion and slope rate

As can be seen from the relationship curve between sediment erosion and slope rate, sediment erosion increases with the increase of slope rate. Under the working condition with a rainfall intensity of 120mm/h, the curve is convex, indicating that sediment erosion increases rapidly at the slope rate of 1:1.25 - 1:1, and slowly at the slope rate of 1:1-1:0.75. Under the working condition with a rainfall intensity of 150mm/h and 180mm/h, the curve is linear, indicating that the increase rate of sediment erosion is relatively consistent.

Regression Analysis

In order to reflect the relationship between sediment erosion and rainfall duration under various working conditions, the nonlinear regression analysis of test data was carried out. Through multiple fitting, the regression equation with the largest determination coefficient was selected, as shown in equation (16). Where, the value of x in the fitting formula is limited to the duration of rainfall in this experiment, i.e. $0 \leq x \leq 60$. The fitting curve is as shown in Figure 8.

$$y = a + b \ln(x + c) \tag{16}$$



(a) Rainfall Intensity-120mm/h (b) Rainfall Intensity-150mm/h (c) Rainfall Intensity-180mm/h
 Fig. 8 - Fitting curve of sediment erosion and rainfall duration

The specific results of nonlinear fitting are shown in Table 2. By observing the determination coefficient R^2 in the table, it is found that it is greater than 0.997 in each working condition, indicating that the nonlinear fitting result is very good, and equation (16) can soundly reflect the relationship between sediment erosion amount and rainfall duration under external-soil spray seeding.

Tab. 2- Regression analysis

| Working Condition | a | b | c | R^2 |
|-------------------|--------------|------------|----------|---------|
| 1 | -5963.61868 | 2214.8242 | 14.66493 | 0.99874 |
| 2 | -6859.74208 | 2649.35689 | 13.18338 | 0.99795 |
| 3 | -13431.63497 | 4314.6354 | 22.38974 | 0.99907 |
| 4 | -3515.05999 | 1443.44149 | 11.31882 | 0.99823 |
| 5 | -5228.44849 | 1998.54593 | 13.57112 | 0.99866 |
| 6 | -10007.57583 | 3307.58463 | 20.48106 | 0.99914 |
| 7 | -2844.49467 | 1129.78831 | 12.31032 | 0.99869 |
| 8 | -3133.98194 | 1365.19371 | 9.85304 | 0.99834 |
| 9 | -9088.22272 | 2885.61775 | 23.12692 | 0.99777 |

At the same time, regression analysis was conducted on the relationship among sediment erosion amount, rainfall intensity and slope rate under the rainfall duration of 60 minutes. Considering that there are few data in each group and the overall trend of the relationship between them is linear, linear equation $y = a + bx$ was selected for regression analysis. The fitting results of the relationship between sediment erosion and rainfall intensity are shown in Figure 9 and equation (17). The value range of x is the rainfall intensity range involved in this test, i.e. $120 \leq x \leq 180$. See Figure 10 and equation (18) for the fitting results of the relationship between sediment erosion and the slope rate, and the value range of x is the slope rate interval involved in this experiment, namely $0.8 \leq x \leq 1.33$.

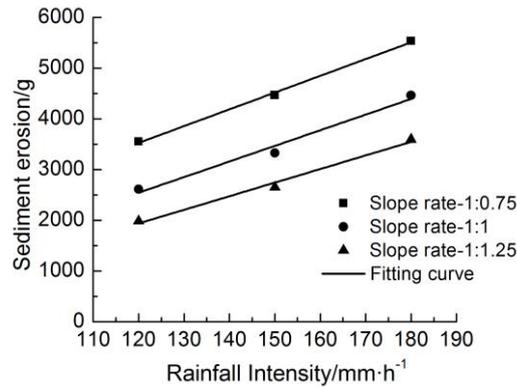


Fig. 9 - Fitting curve of relationship between sediment erosion and rainfall intensity

Slope rate-1:0.75: $y = -439.2 + 33.1x, R^2 = 0.99582$

Slope rate-1:1: $y = -1155.1 + 30.81x, R^2 = 0.96622$ (17)

Slope rate-1:1.25: $y = -1280.3 + 26.8x, R^2 = 0.98092$

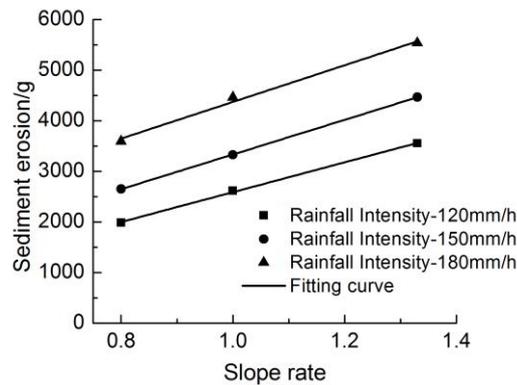


Fig. 10 - Fitting curve of relationship between sediment erosion and slope rate

rainfall intensity-120mm/h: $y = -360.9 + 2948.9x, R^2 = 0.99855$

rainfall intensity-150mm/h: $y = -92.7 + 3425x, R^2 = 0.99994$ (18)

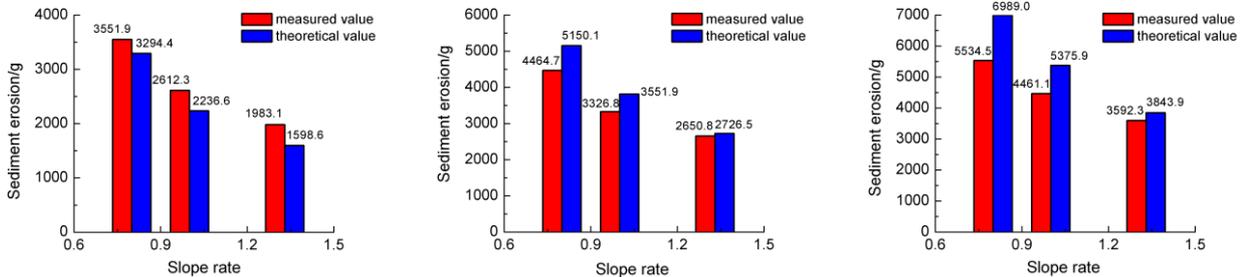
rainfall intensity-180mm/h: $y = 748.2 + 3623.9x, R^2 = 0.98724$

Comparison of Theoretical Calculation and Experimental Results

According to the experimental conditions of scouring test on indoor slope model, reasonably select the parameters in function (11) and put them into the function to calculate the sediment erosion amount under different slope rates and rainfall intensities. The total sediment erosion after 60min of rainfall was selected for comparative analysis, and the theoretical calculation value was compared with the test results as shown in Figure 11.

By comparing the histogram, it can be found that the measured values were greater than the theoretical value under the rainfall intensity of 120mm/h, which is less than the theoretical value under the rainfall intensity of 150mm/h and 180mm/h. The reason for this phenomenon may be that slope collapse phenomenon exists under the rainfall intensity of 120mm/h, this part was collectively counted as the final sediment erosion. It could also be that the rainfall intensity is not

accurately controlled and the rainfall intensity is high. The regularities of the theoretical value and the measured value is consistent, both decrease with the increase of slope rate.



(a) Rainfall intensity-120mm/h (b) Rainfall intensity-150mm/h (c) Rainfall intensity-180mm/h
 Fig. 11 - Comparison of theoretical and measured values

The relative errors under each working condition were collected, as shown in Table 3. It can be seen from the error statistics that the relative error under all other working conditions except for working condition 3 and 7 were all less than 18%. Among which the relative error of working condition 1, 8 and 9 were all less than 10% and that of working condition 8 was only 2.78%, the closest one between theoretical and measured values. The above results shown that the calculation model for sediment erosion derived from hydraulics and the energy method can accurately predict the actual sediment erosion to larger extent, which is of theoretical significance to practical external-soil spray seeding engineering.

Tab. 3- Error statistics

| Working Condition | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-------------------|------|-------|-------|-------|-------|-------|-------|------|------|
| Relative Error/% | 7.82 | 13.31 | 20.81 | 16.80 | 12.77 | 17.02 | 24.05 | 2.78 | 6.56 |

CONCLUSION

- (1) The slope without vegetation is lack of anti-scouring ability after external-soil spray seeding engineering. A large number of gully is formed and slope erosion is relatively serious, surface erosion on the slope is mainly composed of layered erosion and rill erosion, with faster rill developmental rate and obvious surface corrosion phenomenon, effective measures must be taken to avoid engineering failure resulted from heavy rain.
- (2) Sediment erosion of the slope under external-soil spray seeding increases with the increase of rainfall intensity and slope rate. With the increase of rainfall duration, the increase rate remains the same in the first 20min and gradually decreases after 20min. Meanwhile, carried out regression analysis of the experimental data, the equation $y = a + b \ln(x + c)$ can well adapt to the relationship between sediment erosion and rainfall duration, and the equation $y = a + bx$ can well adapt to the relationship among sediment erosion, rainfall intensity and slope rate.
- (3) The calculation model applicable to the sediment of slope under external-soil spray seeding was derived from hydraulics and the energy method, which revised the traditional energy method formula to some extent. By comparing the theoretical value and measured data of the designed test, it is found that the relative error of the theoretical value and measured data under most working conditions is within 18%, which indicating that this calculation model can accurately predict the sediment of slope under external-soil spray seeding.

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