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基于土槽冲刷法的紫色土侵蚀细沟剥蚀率研究*

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摘要 细沟剥蚀率是细沟侵蚀的重要组成部分, 也是确定细沟侵蚀模型的关键参数。通过试验获取紫色土侵蚀细沟水流含沙量随沟长变化的过程数据, 采用数值计算方法和解析计算方法估算细沟剥蚀率。结果表明: 细沟剥蚀率随沟长增加呈幂指数下降; 随含沙量增加呈线性递减。在坡度较陡、流量较大时, 拟合效果更好。用解析法所得结果与用试验数据计算所得结果具有很好的一致性, 表明了数值计算方法和解析法估算细沟剥蚀率均具有合理性, 为紫色土细沟侵蚀过程参数的确定奠定了基础。

关键词 紫色土; 细沟剥蚀率; 沟长; 水流含沙量; 耦合关系

中图分类号 S157.1 **文献标识码** A

土壤剥蚀作用是指由侵蚀动力引起的土壤颗粒从母质由团聚体的自然状态被剥蚀的过程^[1], 它是细沟泥沙的主要来源, 坡面侵蚀量大的地方土壤剥蚀总是很活跃^[2-5]。细沟剥蚀率被定义为单位时间单位面积被径流剥蚀掉的土壤质量^[6], 与水流含沙量间有着密切联系。近几十年来, 国内外学者对细沟形成机制进行了大量研究, 而估算细沟剥蚀率一直是其中的热点问题^[7-9]。

1947年, Ellsion^[10]最早提出了关于含沙量对侵蚀过程影响的概念模型, 认为径流剥蚀土壤的能力随径流中含沙量的增加而增加。此后, Foster和Meyer^[11]提出了一种新的概念模型, 得出径流在低含沙量时, 剥蚀能力大, 随着水流含沙量增加, 剥蚀能力降低, 当水流输沙量等于输沙能力时, 细沟剥蚀率为0; 而输沙量大于输沙能力时, 泥沙开始沉积。Nearing等^[12]从能量分析的角度对Foster和Meyer的概念模型做了进一步阐述, 发展为WEPP模型的核心部分。

国内学者也对细沟侵蚀展开了大量研究, 在黄土高原地区, 关于细沟侵蚀输沙过程的研究方法系统多样, 成果丰富。蔡强国等^[13]通过模拟研究, 较好地预测了细沟侵蚀发生的可能性及侵蚀产沙量。李占斌等^[14]通过土槽冲刷试验, 得出黄土细沟剥蚀率与水流通过坡面的能量损耗关系。张晴雯等^[15]从能量角度分析了不同动力条件下侵蚀产沙量随沟长的变化规律。在同样水力侵蚀严重的紫色土地区, 国内研究人员也展开了相关的研究, 严冬春等^[16, 17]通过野外人工模拟降雨得出紫色土细沟侵蚀在各坡度下的临界沟长, 及临界沟长与坡度的关系, 并总结出以控制细沟发生为核心的“大横坡+小顺坡”耕作模式。耿晓东等^[18]利用室内模拟降雨研究了降雨强度和坡度双因子对紫色土坡面侵蚀产沙过程的影响。前人在紫色土细沟侵蚀研究中, 试验发生条件均集中设定为人工模拟降雨法, 研究多针对所得结果进行描述性探讨, 对细沟侵蚀过程研究偏少。本研究引入黄土地区表现良好的室

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内试验土槽, 装土模拟紫色土耕作层, 通过直接冲刷连续坡长土壤后, 采用改良的体积置换法确定细沟侵蚀量, 研究的尺度相对小, 主要对细沟侵蚀过程进行研究。本文重点研究细沟剥蚀率与细沟沟长、水流含沙量的关系, 为今后紫色土区的侵蚀模型的研究提供依据。

1 材料与方法

1.1 紫色土细沟侵蚀过程数据

通过设计的试验, 获得细沟侵蚀过程数据。具体试验设计方案见参考文献 [19]。试验采用5个坡度(5° 、 10° 、 15° 、 20° 、 25°), 3个流量

(2 Lmin^{-1} 、 4 Lmin^{-1} 、 8 Lmin^{-1})。在给定流量和坡度下, 进行一定时段的水流冲刷、细沟土壤侵蚀后, 在距细沟入口 0.5 、 1 、 2 、 3 、 4 、 5 、 6 、 7 、 8 、 10 和 12 m 处设置共11个点, 分别插入挡板深至犁底层, 将侵蚀细沟分成 $0 \sim 0.5$ 、 $0.5 \sim 1$ 、 $1 \sim 2$ 、 $2 \sim 3$ 、 $3 \sim 4$ 、 $4 \sim 5$ 、 $5 \sim 6$ 、 $6 \sim 7$ 、 $7 \sim 8$ 、 $8 \sim 10$ 和 $10 \sim 12$ 的沟段(如图1所示)。在沟段中将清水分段倒入细沟中, 使清水充满各段细沟中, 测量出每个沟段侵蚀土壤的体积, 而后由土壤容重计算得到侵蚀土壤的质量。通过累积各段土壤侵蚀量。在通过试验过程中的供水流量和时间计算得到供水量, 据此计算得到沿沟长分布的紫色土细沟侵蚀含沙量随沟长的分布过程。

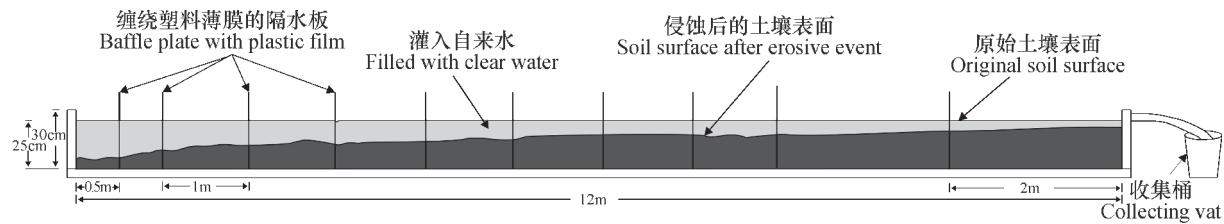


图1 体积置换法示意图^[20]

Fig. 1 Sketch of the volume substitution method

典型的侵蚀细沟水流含沙量随沟长的分布过程见参考文献[19]。各工况下水流含沙量与距离的关系可用如下关系是拟合:

$$c = A(1 - e^{-Bx}) \quad (1)$$

用式(1)拟合的参数A、B及 R^2 如表1所示。

1.2 细沟剥蚀率数值计算方法

从定义上看, 当细沟侵蚀达到稳态时, 在细沟的给定部位径流驱动力一定, 细沟剥蚀率随所处细沟位置变化但不随时间变化。不同部位细沟产沙量只与其距细沟起始位置有关^[21, 22]。在距离起始位置x处, 水流含沙量为c, 则在细沟距起始位置距离为 $x + \Delta x$ 时, 水流含沙量为 $c + \Delta c$ 。即沟长增加 Δx 水流含沙量增加 Δc 。由此, Δx 段细沟的平均土壤剥蚀率^[6]为:

$$D_r \approx q \frac{\Delta c}{\Delta x} \quad (2)$$

式中, D_r 为 Δx 段细沟的平均土壤剥蚀率; q 为单宽流量; Δx 为细沟沟长变化量; Δc 为细沟沟长增加 Δx 时水流含沙量的增加量。

1.3 细沟剥蚀率解析计算方法

由式(1)可以得到细沟剥蚀率的解析计算公式为:

$$D_r = \lim_{\Delta x \rightarrow 0} \left(\frac{q \Delta c}{\Delta x} \right) = q \frac{dc}{dx} \quad (3)$$

将式(1)代入式(3)中, 得到:

$$D_r = ABqe^{-Bx} = a_2 e^{-Bx} \quad (4)$$

由式(1)和式(4)推导得到细沟剥蚀率与含沙量的关系如下:

$$D_r = ABq - ABq e^{-Bx} \quad (5)$$

$$D_r = ABq - Bqc = d_2 + e_2 c \quad (6)$$

式中, d_2 为最大剥蚀率, $\text{kgm}^{-2}\text{s}^{-1}$; e_2 为细沟剥蚀率随含沙量减小的比例系数, m^3kg^{-1} 。

式(4)即为解析计算细沟剥蚀率与细沟沟长关系的表达式, 而式(6)为解析计算细沟剥蚀率与细沟含沙量关系的表达式。根据上述两个公式, 只需要知道泥沙含量与细沟沟长的关系, 就能分别用式(4)和式(6)解析计算得出细沟剥蚀率, 并

表1 水流含沙量随细沟沟长变化拟合参数^[19]

Table 1 Relationship between the length of fitting parameters of sediment concentration and ditch

| 坡度 Slope gradient/ (°) | 流量 Flow rate/ (L min ⁻¹) | 拟合参数 Regression parameters | | 决定系数 Coefficient of determination <i>R</i> ² |
|---------------------------|---|-------------------------------|------|---|
| | | A | B | |
| 5 | 8 | 206.6 | 0.25 | 0.98 |
| | 4 | 274.4 | 0.28 | 0.93 |
| 10 | 8 | 296.9 | 0.31 | 0.96 |
| | 2 | 387.3 | 0.41 | 0.99 |
| 15 | 4 | 456.9 | 0.43 | 0.99 |
| | 8 | 533.0 | 0.64 | 0.99 |
| | 2 | 395.8 | 0.64 | 0.98 |
| 20 | 4 | 476.8 | 0.70 | 0.99 |
| | 8 | 548.6 | 0.57 | 0.96 |
| | 2 | 451.7 | 0.41 | 0.99 |
| 25 | 4 | 499.2 | 0.62 | 0.96 |
| | 8 | 595.1 | 0.51 | 0.99 |

拟合得到细沟剥蚀率分别与细沟沟长、细沟含沙量的关系。

2 结 果

2.1 细沟剥蚀率与细沟沟长的耦合关系

绘制由试验数据计算得到的细沟剥蚀率与沟长的拟合关系图(图2)。根据图中散点分布情况,选择幂函数进行拟合: $D_r=a_1e^{-b_1x}$, 式中, a_1 、 b_1 均为回归系数。

从图2所示试验值拟合结果可以看出,除个别坡度、流量较小的情况外,决定系数(R^2)均大于0.8,说明拟合效果较好。在同一坡度下,回归系数 a_1 随流量增大而增大,回归系数 b_1 也基本呈相同的变化趋势。表明,紫色土细沟剥蚀率随沟长的增大呈指数减少。回归系数 a_1 越大细沟剥蚀率越大,即 a_1 越大,土壤侵蚀越大。回归系数 b_1 代表细沟剥蚀率的衰减速度, b_1 越大则说明细沟剥蚀率随沟长的增长,其减小的速率加快。图2试验值拟合结果表明,细沟起始处入流的清水具有最大的剥蚀能力。随着沟长的增加,细沟剥蚀率逐渐降低,最后趋于0。从拟合曲线的走势可得出细沟剥蚀率减小的速率在细沟开始端最大,而后逐渐减缓至0。主要原因是随着细沟侵蚀过程的进行,水流含沙量增

加,水流不仅需要克服沟底阻力,还要搬运剥蚀泥沙,同时发生新的剥蚀泥沙过程,致使细沟剥蚀率逐渐减小,最后趋于0。依据能量守恒定律,水流从细沟入口流经细沟出口的过程中,水流需搬运已被剥蚀的土壤颗粒,这势必导致用于剥蚀作用的能量减少。

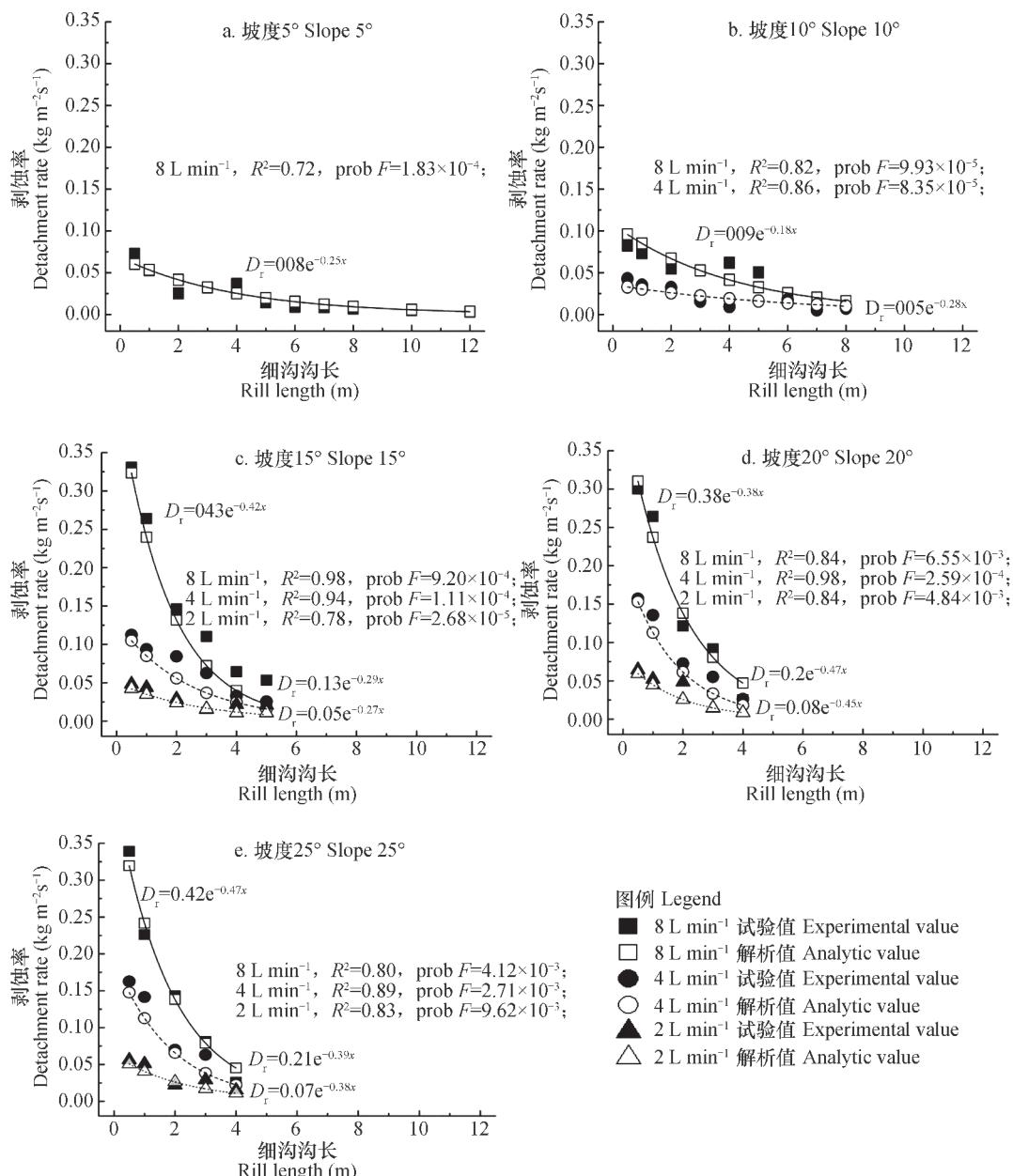
为了定量评估清水回填试验估算值的准确性,运用水流含沙量计算公式 $c=A(1-e^{-Bx})$,拟合水流含沙量和沟长的关系,得到回归系数 A 、 B ^[19]。然后将相关参数代入式(4),解析地计算细沟剥蚀率,所得结果与试验数据估算结果进行对比,如图2所示。

图中试验所得数据与解析法计算得到的数据重合度越高说明试验数据估算细沟剥蚀率越准确。从图2可以看出,各水力条件下试验数据点与解析法计算的数据点大部分很接近,表明试验数据估算细沟剥蚀率所得的结果与解析法计算细沟剥蚀率吻合良好。使用解析法得到的细沟剥蚀率与沟长的关系曲线与试验数据所得曲线大致相同,表明了两者具有较好的一致性。

2.2 细沟剥蚀率与水流含沙量的耦合关系

采用下式拟合细沟剥蚀率(D_r)与泥沙含量(c)的关系如下:

$$D_r=f+gc \quad (7)$$



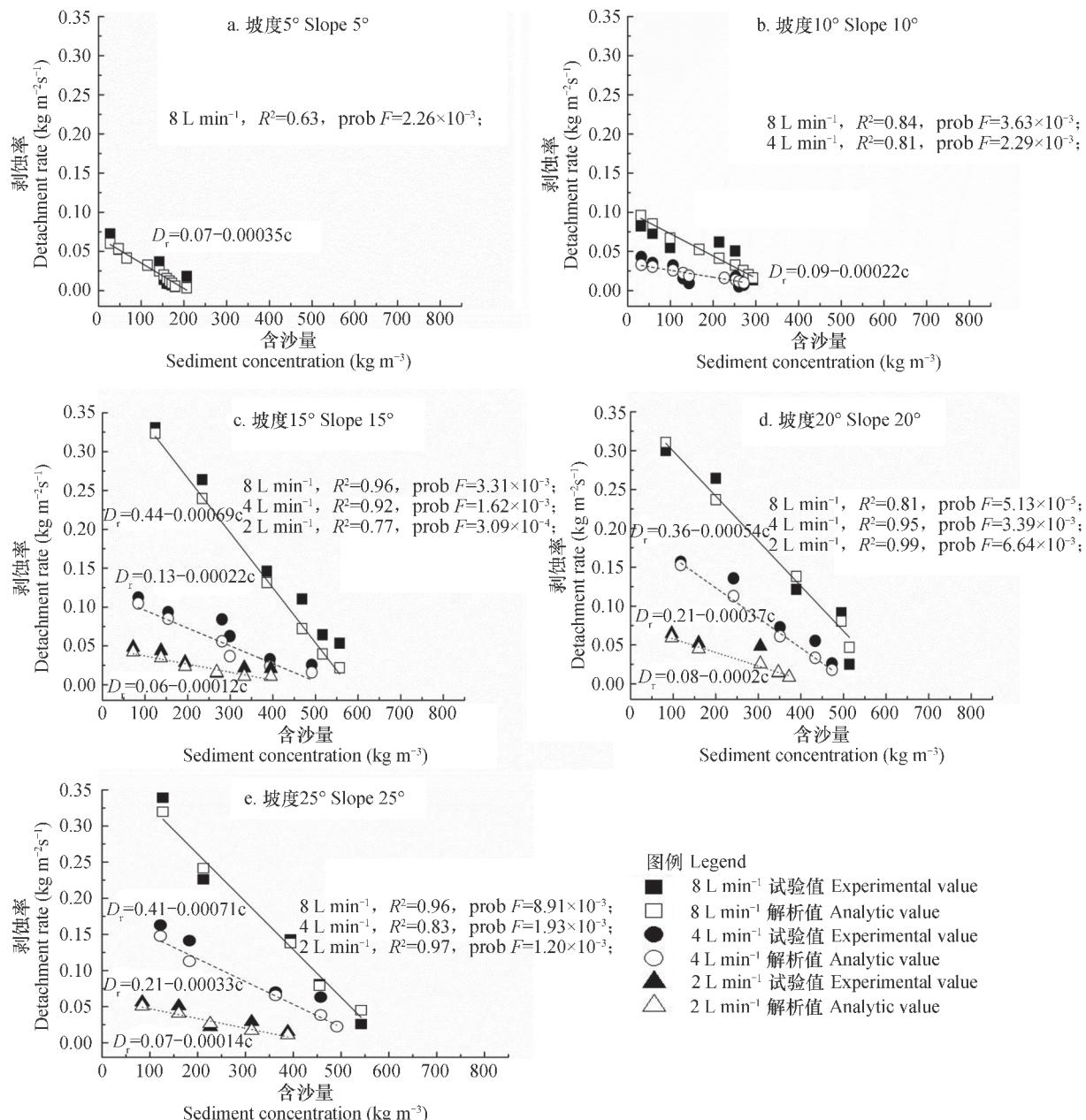
注：图中拟合公式为试验值拟合公式， D_r 为剥蚀率； x 为细沟沟长； R^2 为决定系数；prob F 为 F 检验值
Note: The fitting formulas were fitted by experimental values in the figures, D_r is the Detachment rate; x is the Rill length; R^2 is the Determination coefficient; prob F is the F test value

图2 细沟剥蚀率与沟长的耦合关系

Fig. 2 Rill detachment rate as a function of rill length

式中， f 、 g 为回归系数； c 为泥沙含量， kg m^{-3} 。拟合结果如图3所示。从图中试验值拟合结果可知，在相同坡度下，随流量的增加回归系数 f 和 g 的绝对值均增大。决定系数(R^2)在个别缓坡、小流量情况下较低，其余情况均在0.8以上，表明整体拟合效果较好。另由式(7)可知，当含沙量 c 为0时，水流细沟剥蚀率最大，此时 $D_r=f$ ，则 f 即为最大剥蚀率， f 增大表示最大剥蚀率增加。

如图3试验值拟合结果所示，细沟剥蚀率与水流含沙量成反比关系，水流含沙量较小时细沟剥蚀率较大。在细沟起始端，清水的含沙量为0，细沟剥蚀率最大，验证了清水具有最大剥蚀能力。此后，清水开始剥蚀泥沙，水流含沙量逐渐增加，水流剥蚀能力相应降低。在水流含沙量接近达到径流输沙能力条件下的含沙量时，细沟剥蚀率趋于0。并且在坡度相同时，流量越大，细沟剥蚀率随泥沙



注：图中拟合公式为试验值拟合公式， D_r 为剥蚀率； c 为水流含沙量； R^2 为决定系数；prob F 为 F 检验值 Note: The fitting formulas were fitted by experimental values in the figures, D_r is the Detachment rate; x is the Rill length; R^2 is the Determination coefficient; prob F is the F test value

图3 细沟剥蚀率与含沙量的关系

Fig. 3 Rill detachment rate as a function of sediment concentration

含量的增大下降的越快。同时相同流量下，坡度越陡细沟剥蚀率递减速率也越快。其中一部分原因是在细沟起始处，入流的为清水，其全部能量均用来剥蚀土壤颗粒，随着细沟水流中含沙量逐渐增加，水流将分配一部分径流能量用于携带和搬运土壤颗粒，用于剥蚀作用的能量势必减少。

运用水流含沙量计算公式所得回归系数A、

B，并基于试验数据和解析式(6)所计算的细沟剥蚀率所得结果如图3所示。从图3可以看出，在不同水力条件下，试验数据估算的数据点与解析法计算的数据点大部分均较为接近，表明试验数据估算的细沟剥蚀率与理论解析法计算细沟剥蚀率吻合良好。总体而言，试验估算值与解析法计算值较为接近，表明了两者具有较好的一致性。

3 结 论

本研究将试验获得的水流含沙量随沟长变化的数据，用于研究紫色土细沟侵蚀剥蚀率，反映紫色土细沟侵蚀的动态过程。利用此方法估算了紫色土在5个坡度（ 5° 、 10° 、 15° 、 20° 、 25° ）及三个流量（2、4、 8Lmin^{-1} ）下的细沟剥蚀率。计算结果说明，紫色土细沟剥蚀率随沟长增加呈幂指数下降，随含沙量的增加呈线性减少，此规律在陡坡及大流量下趋势更为明显。通过解析法计算细沟剥蚀率，分别与试验数据计算得到细沟剥蚀率与沟长、细沟剥蚀率与含沙量的关系两两对比，得出试验估算值与解析计算值有较好的一致性，说明了本研究所采用的试验方法有效、可行。

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Based on the Soil Flume Flushing Method to Study the Rill Detachment Rate of Purple Soil

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Abstract In the past decades, a large volume of research work has been done on mechanism of rill formation by domestic and foreign scholars. Soil detachment as the main source of rill sediment is also a hot issue of the research on rill erosion. Being an important parameter of rill erosion models, like WEPP, soil detachment rate has also been a focal point in the research on rill erosion. In this article, experimental and analytic methods were proposed and tested for use in calculating rill detachment rate, with a view to defining suitable principles and methods for computing rill detachment rates in the purplish soil region and enriching the basic research on rill detachment rate in purple soil with theories. The research adopted the in-lab soil flume scouring experiment, using flumes 12m in length each. The flumes were packed with purplish soil to form a sheet of plow layer over a simulated purplish subsoil layer low in permeability. The experiment was designed to have five slope gradients for the flumes (5° , 10° , 15° , 20° and 25°) and three water flow rates (2 Lmin^{-1} , 4 Lmin^{-1} and 8 Lmin^{-1}). Water flow rates in the experiment were set in the light of the critical intensities of the rainfalls that produce rill erosion in sloping croplands on purple soil. Sediment was collected in a sampling bucket placed at the rill outlet. After a certain period of water scouring, rill erosion occurred, and then the soil flume was adjusted from sloping to horizontal. Plastic film was folded into multiple layers to form eleven thin, waterproof baffle plates the same in width as the rill. The baffle plates were inserted at 0.5 m, 1 m, 2 m, 3 m, 4 m, 5 m, 6 m, 7 m, 8 m, 10 m, and 12 m from the rill entrance, thus dividing the erosion rill into the 11 sections: 0~0.5 m, 0.5~1 m, 1~2 m, 2~3 m, 3~4 m, 4~5 m, 5~6 m, 6~7 m, 7~8 m, 8~10 m and 10~12 m.

m. The baffle plates were inserted deep enough to prevent water from flowing between the rill sections. Each section of the rill was then filled with water and by calculating volume of the water in the rill, the soil erosion volume was worked out section; then quantity of the soil erosion was figured out from bulk density of the packed soil. Rill erosion was found to be quite low on a slope 5° in gradient with a flow rate of 8 Lmin^{-1} , thus excluding the need of running the test with flow rates being lower than 8 Lmin^{-1} , that is, 2 Lmin^{-1} or 4 Lmin^{-1} , on the slope. Similarly, the test with the flow rate of 2 Lmin^{-1} on a slope 10° in gradient, because erosion was already very low with flow rate at 4 Lmin^{-1} . All the other combinations of gradients and flow rates were tested, forming a total of twelve sets of experimental conditions. Each test had three replicates, thus making up a total of 36 separate trials. A series of process data were obtained through the experiment, and then rill detachment rates were calculated relative to hydraulic condition. On such a basis the relationships of rill detachment rate with rill length distribution process and sediment concentration were simulated. Results of the simulation show that rill detachment rate decreased exponentially with growing rill length, and linearly with rising sediment concentration. In the flumes higher in slope gradient and in flow rate, too, the effect of the simulation was better. Rill detachment rates were calculated with the analytic method and compared with those obtained through the experiment in their relationships with rill length and sediment concentration. It was found that the estimation through the experiment agreed well with the calculation using the analytic method, which indicates that the experimental method used in this research is effective and feasible.

Key words Purple soil; Rill detachment rate; Sediment concentration; Coupling relations

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