

三峡库区碎石含量对紫色土容重和孔隙特征的影响*

王小燕¹ 蔡崇法^{2†} 李 鸿¹ 谢德体¹

(1 西南大学资源环境学院三峡库区生态环境教育部重点实验室, 重庆 400715)

(2 华中农业大学资源与环境学院水土保持研究中心, 武汉 430070)

摘 要 土壤容重和孔隙分布特征是土壤重要的基本物理性质, 但有关含碎石土壤的物理性质以及碎石含量对土壤结构影响的研究尚不多见。三峡库区紫色土中存在大量的碎石, 为了深刻了解和评价土壤中碎石对容重与大孔隙形成的可能作用, 通过野外调查、典型土样采集和室内分析实验, 探讨了三峡库区典型土地利用类型下土壤中的碎石体积含量以及不同粒径碎石的基本物理性质及其对土壤容重和孔隙特征的影响。结果表明: 土壤中碎石的孔隙度和饱和含水率随着碎石粒径的减小而增大, 小碎石本身具有一定的持水、供水性能; 碎石含量对土壤的总容重、细土容重有显著影响, 随着碎石含量的增加, 土壤的总容重逐渐增加, 而细土容重与碎石含量呈线性负相关关系, 土壤中碎石的存在有利于改善土壤的结构; 土壤孔隙分布特征与碎石含量密切相关, 随着碎石含量的提高, 土壤总孔隙度和毛管孔隙度呈减少趋势, 而非毛管孔隙度即大孔隙呈增加趋势, 碎石的存在有利于改善土壤的透水性能。本研究为山区农用地灌溉与水分管理提供了科学依据。

关键词 紫色土; 碎石; 容重; 孔隙; 三峡库区

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受成土过程和人为活动的影响, 碎石 (> 2 mm) 在土壤中有着广泛的分布。碎石的分布对土壤的化学风化速率^[1]、养分供给^[2]、水文响应^[3-4]以及表土侵蚀速率^[5]等均有重要影响。土壤中碎石通过各种方式影响土壤水蚀过程, Poesen 等^[6]将这些影响方式分为直接影响和间接影响。碎石对土壤侵蚀的直接影响包括保护表土免受雨滴击溅和径流冲刷的分散, 或拦截溅散的泥沙; 碎石间接影响土壤侵蚀的方式多种多样, 主要包括以下几个方面: (1) 改变会影响土壤侵蚀过程中土壤物理性质 (如容重、孔隙度等), (2) 影响表层土壤的物理退化过程 (如表土结皮等), (3) 影响与径流产生及流量等有关的水文过程 (如入渗和

渗透), (4) 径流的水力特性。同时是否考虑土壤中碎石, 土壤中的有效含水量、土壤水渗漏到地下水中的量以及植物能吸收的有效水含量存在很大的差异^[7-8], 在研究含碎石土壤的各种性质时不能忽略碎石的存在。以往研究很少有对碎石与容重和土壤孔隙之间关系做出直接的解释, 而且以往的土壤大孔隙研究也多是在土壤质地相对均一的条件下进行的, 对以物理风化为主、土壤发育程度不深、碎石含量很高的坡地紫色土中碎石在土壤大孔隙形成中作用的研究还相当缺乏。本研究旨在了解三峡库区紫色土中的碎石对土壤容重和孔隙特征的影响及其可能的作用机制, 为建立准确预报、模拟径流和土壤侵蚀的时空变化规律的模型提供土壤空间分

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† 通讯作者 Corresponding author, E-mail: cfeai@mail.hzau.edu.cn

† 作者简介: 王小燕 (1983—), 女, 四川岳池人, 博士, 讲师, 主要从事水文土壤学、土壤侵蚀与水土保持方面研究。

E-mail: wxy8388@gmail.com

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布的基本参数,也为流域治理和土壤保护提供理论依据。

1 材料与方法

1.1 研究区概况

本文的研究对象是三峡库区的紫色土,试验区位于三峡库区秭归县王家桥小流域。王家桥小流域位于 $31^{\circ}05' \sim 31^{\circ}15'N$, $110^{\circ}40' \sim 110^{\circ}47'E$,属于长江二级支流,距长江约9 km。流域总面积 16.7 km^2 ,自北偏东向南偏西呈窄条状,南北长7 km,东西宽3.5 km。三峡库区年平均气温为 $17 \sim 19^{\circ}C$,年降水量 $1\ 000 \sim 1\ 250 \text{ mm}$,降雨集中在4—10月,特别是5—9月常有暴雨出现。流域海拔为 $184 \sim 1\ 180 \text{ m}$ 。流域坡度较陡, $25^{\circ} \sim 35^{\circ}$ 的坡地占35%,大于 35° 的坡地占50%,以柑橘种植为主,属典型的山区小流域。该流域出露地层为侏罗系蓬莱镇组紫灰色石英砂岩、棕紫色灰质砂岩与棕紫色泥岩互层,含透镜状砾岩及硅化木,土壤为中性和石灰性紫色土^[9]。紫色母岩一经出露地表,在光、热、水等自然因素的作用下,迅速发生物理风化。据观测,一般可发现需经历以下几个物理风化特征阶段:岩层—崩解—碎屑化—成壤(土)—化泥^[10]。紫色土在发生分类上称初育土,在系统分类上分属新成土和雏形土。在土壤性质上是一种特殊的土壤类型,快速风化是其中的一大特殊性质之一。蓬莱镇组的成土速率较大,可达 $12\ 000 \text{ t km}^{-2} \text{ a}^{-1}$ ^[11]。该区紫色土表现出土层薄、碎石含量高特点,具有坡地紫色土的典型特点。

1.2 土壤与碎石基本物理性质的测定

关于样点的布设与样品采集以及碎石体积含量测定详见笔者已发表论文《三峡库区紫色土碎石分布特征》^[12]。

在分析含碎石土壤特性时,需要区别两个容重概念:总容重和细土容重。总容重和细土容重的测定:将采取土样($30 \text{ cm} \times 30 \text{ cm} \times 20 \text{ cm}$)($V_{\text{总}}$)烘干称重获得含碎石土壤总质量 $m_{\text{总}}$;将通过水洗法获得的碎石采用排水法获得碎石体积 $V_{\text{碎石}}$;将碎石烘干称重获得碎石质量 $m_{\text{碎石}}$,最后通过式(1)和式(2)计算含碎石土壤的总容重和细土容重:

$$\text{总容重} \text{BD}_T = \text{土壤总质量} m_{\text{总}} / \text{土壤总体积} V_{\text{总}} \quad (1)$$

$$\text{细土容重} \delta_f = (\text{土壤总质量} m_{\text{总}} - \text{碎石质量} m_{\text{碎石}}) / (\text{土壤总体积} V_{\text{总}} - \text{碎石体积} V_{\text{碎石}}) \quad (2)$$

碎石基本物理性质的测定:随机选取不同粒径级别的碎石各10颗,放入温度设定为 105° 的烘箱内,24 h后取出称重获得碎石烘干质量 m_0 ;常温下将碎石浸泡于纯净水中24 h,使碎石充分吸水称重,获得碎石饱和含水质量 m_1 ;在碎石表面涂抹一薄层防水的石蜡,再通过排水法获得碎石的体积 v ,最后通过下列各式计算碎石的密度、孔隙度和饱和含水率:

$$\text{碎石密度} \text{BD}_{\text{碎}} = \text{碎石烘干质量} m_0 / \text{碎石体积} V_{\text{碎石}} \quad (3)$$

$$\text{碎石孔隙度} P_{\text{碎}} = (\text{碎石饱和含水质量} m_1 - \text{碎石烘干质量} m_0) / \text{纯水密度} \rho / \text{碎石体积} V_{\text{碎石}} \quad (4)$$

$$\text{碎石饱和含水率} \text{SW}_{\text{碎}} = (\text{碎石饱和含水质量} m_1 - \text{碎石烘干质量} m_0) / \text{碎石烘干质量} m_0 \quad (5)$$

2 结果与讨论

2.1 碎石的基本物理性质

紫色土中的碎石一般为紫色泥岩、页岩或砂岩、泥砂岩风化的产物,形状以不规则块状为主,少量为长棱形、片状。紫色母岩的矿物组成一般较为复杂,在干湿交替、冷热循环条件下,不同的导热率和胀缩性加剧了紫色母岩的物理风化速度。岩石首先从大块状龟裂风化为大于2 mm的碎屑(碎石)成为疏松多孔的土壤母质,具备了一定的水贮存运移能力。紫色岩碎石继承了紫色母岩的性质,风化程度的差异,导致其密度、孔隙度和饱和含水率的差异。图1显示了小、中、大三种粒径碎石的密度、孔隙度和饱和含水率,不同粒径碎石的密度、孔隙度和饱和含水率有显著差异。不同粒径碎石的风化程度不同,随着碎石粒径的增大,碎石的风化程度降低,其密度逐渐增大,依次为 1.9 、 2.2 、 2.3 g cm^{-3} (图1a),而碎石的孔隙度和饱和含水率逐渐减少,小碎石、中碎石和大碎石的孔隙度依次为 0.16 、 0.10 、 $0.06 \text{ cm}^3 \text{ cm}^{-3}$ (图1b),三种粒径碎石的饱和含水率依次为 8.0% 、 4.5% 、 3.2% (图1c),这与李燕等^[13]的研究结果相一致。在分析土壤水分性质与预测土壤有效水分含量时,碎石所持有的水分常常被忽略不计,但在含碎石土壤中,特别是当碎石含量较高时,这部分水分具有重要的作用。在石质山区,植物吸收的水分以及蒸腾所需水分大部分来自岩石裂缝渗水。干旱条件下,植物所吸收的水分大部分来自深度风化的岩石^[14]。有研究进一步指出,与表层土壤相比,

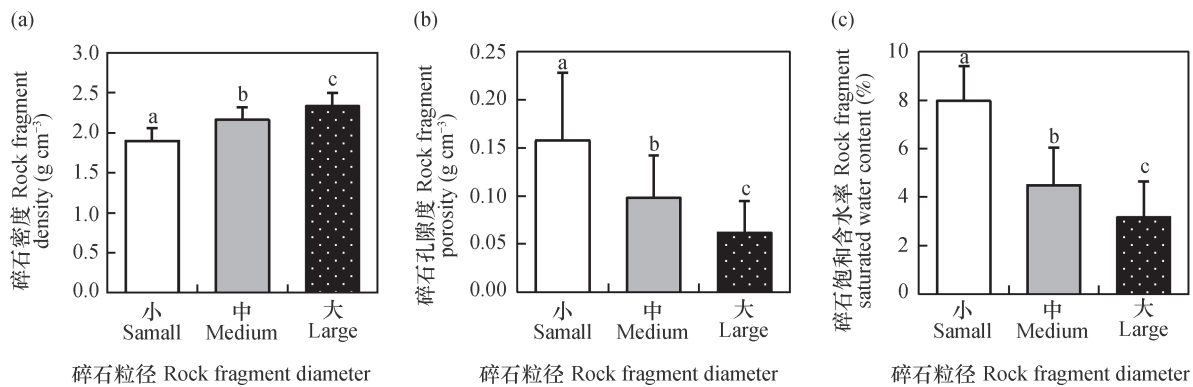


图1 不同粒径碎石密度 (a)、孔隙度 (b) 与饱和含水率 (c)

Fig. 1 Density (a), porosity (b) and saturated water content (c) of rock fragments relative to particle size

底层的风化岩石能为作物生长提供更多的有效水分^[15-16]。Hubbert等^[17]的研究也表明,在含碎石土壤中,土壤中的碎石为植物生长提供了70%的水分。

2.2 含碎石土壤的容重

分析含碎石土壤A(0~20cm)、B(20~40cm)、C(40~60cm)、D(60~80cm)各土层的容重,结果显示,随着土层加深,土壤总容重和细土容重提高(图2)。大量研究结果表明,随着土层深度的增加,由于土壤愈加紧实,土壤有机质含量降低,团聚体减少,且植物根系量显著降低等原因,土壤容重逐渐加大^[18-19]。

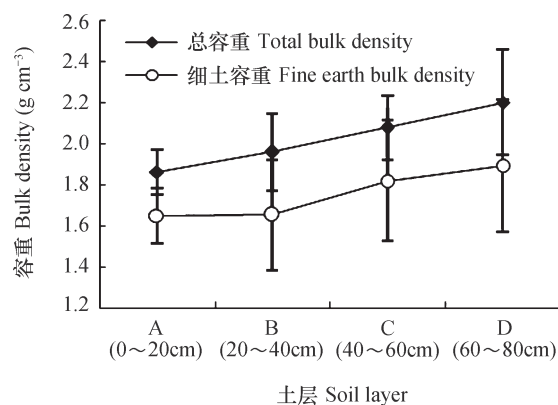


图2 不同土层含碎石土壤的总容重和细土容重

Fig. 2 Total bulk density and fine earth bulk density of soils containing rock fragments for different soil layers

从图3可以看出,在各土层,随着碎石含量的增加,含碎石土壤的总容重逐渐增加(图3a),而含碎石土壤的细土容重逐渐减少(图3b)。碎石与细土容重呈负相关关系可归因于以下几个方面:(1)当碎石含量较高时,可能会出现细土物

质未完全充填碎石之间空隙的情况,从而降低细土容重;(2)在两种级别粒径颗粒的混合物中,小部分大颗粒体的出现均能减少细颗粒组成部分的容重,因为小颗粒体与大颗粒体之间不可能像它们自身那样紧密结合^[20];(3)在干湿交替或冻融与解冻交互的过程中,细土和碎石反应方式不同,这也可能引起碎石和细土之间形成孔隙^[21];(4)土壤中碎石的存在改变了细土部分的性质,随着碎石含量的增加,腐烂的有机质、肥料投入和雨水等集中分布在逐渐减少的细土中^[22]。而单位细土的投入物质增加将会影响其他的土壤性质,如土壤结构等。特别是细土部分有机质含量的增加(与碎石含量增加相对应)会导致细土容重的降低,因为有机质的平均密度较低,大约为224 kg m⁻³^[23]。除了这个影响,有机质含量的增加还常常会使细土部分形成一个更好(如更高的孔隙度)更稳定的结构。图3说明了,即便是在土壤总容重较高的条件下,细土容重也不会特别高,这对植物的生长具有重要意义:如果植物生长与细土部分的物理性质有关,那么砾质土/石质土较高的总容重并不一定意味着恶劣的根系生长环境^[24]。大量研究表明,无论是从经验上还是理论上细土容重均随着碎石含量的增加而降低^[20, 25-26]。Torri等^[27]利用Stewart等^[20]与Alberto^[25]发表的有关森林与农业土壤的调查数据,建立了碎石质量含量与细土容重的函数关系

$$\delta_f = \delta_f^0 (1 - 1.67M_r^{3.39}) \quad (6)$$

式中, δ_f 为含碎石土壤的细土容重; δ_f^0 为不含碎石的土壤容重; M_r 为土壤中的碎石质量含量。式中关键参数 δ_f^0 可通过Rowls^[23]提出的土壤转换函数,根据土壤的质地及有机质含量推算获得。碎石的质量

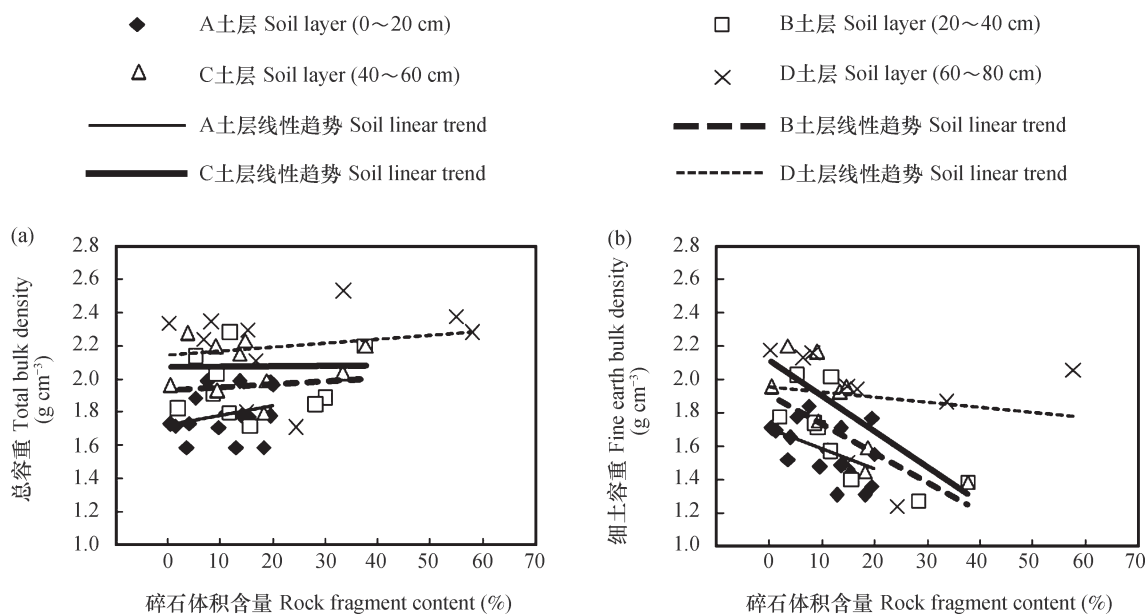


图3 不同土层碎石含量与总容重 (a) 和细土容重 (b) 的关系

Fig. 3 Relationships of rock fragment content with total bulk density (a) and fine earth bulk density (b) in different soil layers

含量和体积含量可以通过下列公式进行换算^[22]

$$V_r = M_r \cdot BD_t / BD_{rf} \quad (7)$$

式中, V_r 为土壤碎石体积含量, BD_t 为土壤总容重, BD_{rf} 为碎石密度。

2.3 含碎石土壤孔隙分布特征

图4显示了A、B、C、D各土层的孔隙分布特征。从该图可以看出,各土层的总孔隙、非毛细孔隙度、毛细孔隙度随土层深度增加而降低。这与大量已发表的研究结果相一致,土层越深,土壤体积质量越大,孔隙度降低^[28-29]。

下面将根据不同土层分析碎石含量与土壤孔隙分布特征的关系。图5显示了碎石体积含量与总

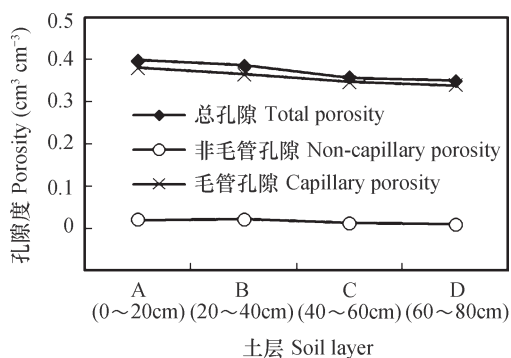


图4 不同土层含碎石土壤的总孔隙度、非毛细孔隙度和毛细孔隙度

Fig. 4 Total porosity, non-capillary porosity and capillary porosity for different soil layers

孔隙度、非毛细孔隙度和毛细孔隙度的关系,从该图可以看出,随着碎石体积含量的提高,土壤总孔隙度和毛细孔隙度呈减少趋势(图5a、图5c),而非毛细孔隙度呈增加趋势(图5b)。时忠杰等^[30]在黄土区的研究也指出,碎石体积含量增加导致土壤大孔隙的平均半径和体积增大,特别是导致半径大于1.4 mm的大孔隙密度的增大。目前,有不少学者研究了土壤中碎石存在对水分入渗和渗透过程的影响,有研究结果指出土壤中碎石的存在减少了水分入渗^[31-33]。Zhou等^[34]的研究还得出碎石对土壤水分运动的影响存在一个阈值,当碎石含量小于40%时,入渗速率和饱和导水率随着碎石含量的增加而降低,当碎石含量超过40%时,则随碎石含量的增加而增加。王慧芳和邵明安^[35]采用简单相关分析研究碎石粒径对入渗过程的影响,得出粒径2~3 mm碎石与入渗过程呈显著负相关关系,而>25 mm碎石有利于入渗。这可归因于土壤中碎石存在对土壤总孔隙度和非毛细孔隙度的不同影响。随着碎石含量的增加,土壤总孔隙度减少,这表明了土壤中碎石的存在将减少水分的过水断面;同时,非毛细孔隙度随着碎石体积含量的增加而增加,而非毛细孔隙有利于水分运动,还会促进优先流的形成,从而提高土壤的入渗速率和渗透速率,土壤中碎石的存在是促进入渗还是降低入渗最终取决于这两种相反影响的交互作用。

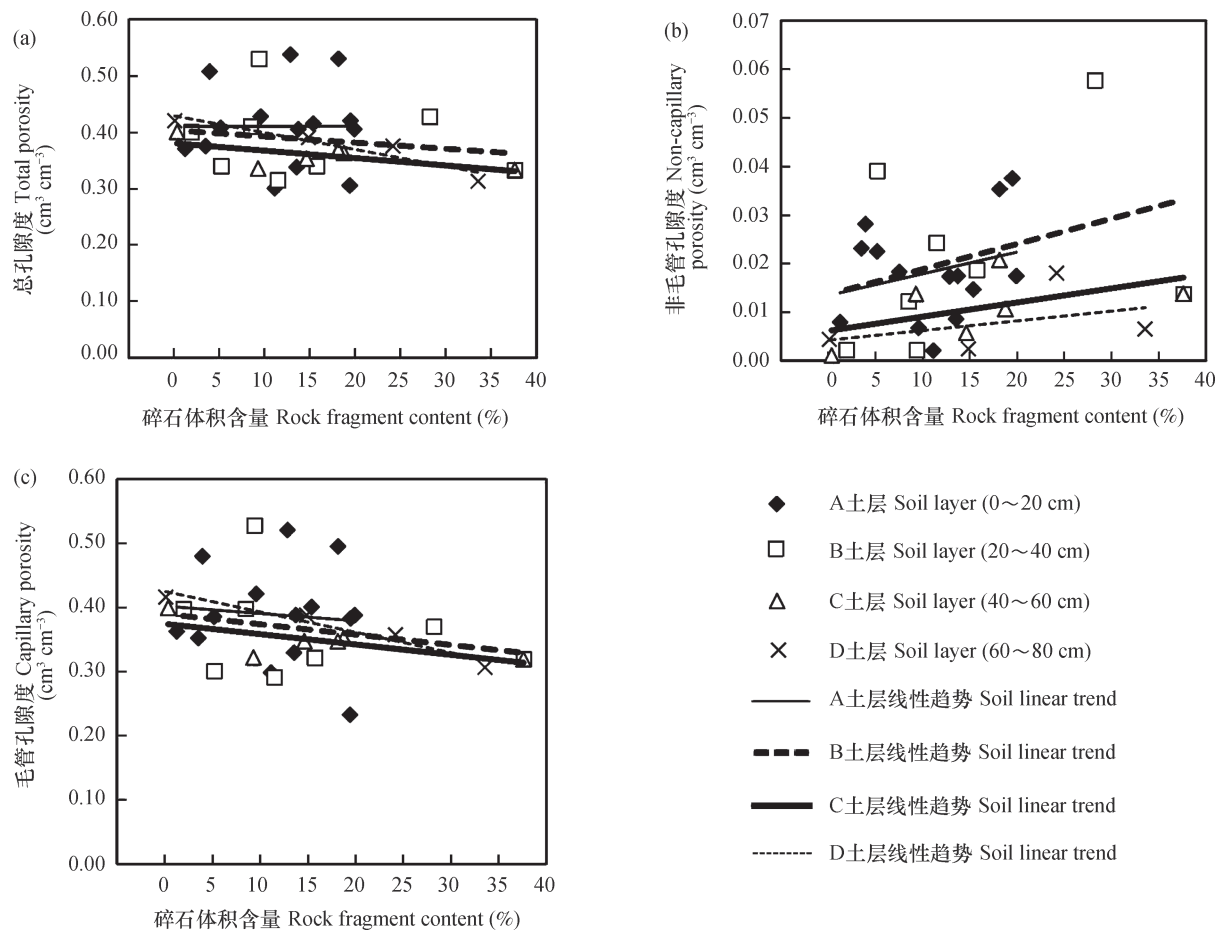


图5 不同土层碎石含量与总孔隙度 (a)、非毛管孔隙度 (b) 和毛管孔隙度 (c) 的关系

Fig. 5 Relationships of rock fragment content with total porosity (a), non-capillary porosity (b) and capillary porosity (c) in different soil layers

3 结论

土壤中碎石的性质及其对土壤性质的影响, 是碎石对水文过程和侵蚀过程产生作用的基础。通过对三峡库区典型山地紫色土含碎石原状土的基本物理性质进行调查, 得出了以下结论: 碎石的粒径越小, 其风化程度越高, 碎石孔隙度和饱和含水率随着粒径的减小而增大。碎石和细土两种不同数量级粒径颗粒的混合, 改变了土壤的结构, 碎石含量对土壤的总容重、细土容重有显著影响。随着碎石含量的增加, 土壤的总容重逐渐增加, 而细土容重与碎石含量呈线性负相关关系。土壤孔隙分布与碎石含量有关。随着碎石含量的提高, 土壤总孔隙度和毛管孔隙度呈减少趋势, 而非毛管孔隙度呈增加趋势。

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Influence of Rock Fragments on Bulk Density and Pore Characteristics of Purple Soil in Three-Gorge Reservoir Area

WANG Xiaoyan¹ CAI Chongfa^{2†} LI Hong¹ XIE Deti¹

(1 Key Laboratory of Eco-environments in Three Gorges Reservoir Region, Ministry of Education, College of Resources and Environment, Southwest University, Chongqing 400715, China)

(2 Soil and Water Conservation Center, College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China)

Abstract 【Objective】 Bulk density and pore distribution characteristics are two fundamental soil properties. However, not much has been reported about physical properties of soils containing rock fragments and influences of rock fragments in soil on bulk density and formation of non-capillary porosity of the

soil. Purple soil is the major type of soil in the Three-Gorge Reservoir Region and the high content of rock fragments is one of the important characteristics of the purple soil. The existence of plentiful rock fragments in the soil will sure affect the formation of bulk density and porosity characteristics. The purpose of this study is to understand how rock fragments affect bulk density and porosity characteristics and its possible mechanism in the purple soil of the region. It is expected that the findings in this study may help collect some basic parameters of soil spatial distribution for building models to be used to predict spatio-temporal variation of surface runoff and soil erosion, while providing some scientific bases for irrigation and water management of agricultural land in mountainous areas. **【Method】** In order to explore in depth and evaluate potential effects of rock fragments on bulk density and porosity characteristics, soil samples typical of the soil were collected during field surveys for in-lab analysis of contents and fractions of rock fragments in particle size, soil physical properties, bulk density and porosity. **【Result】** (1) Rock fragments varied sharply in density, porosity, saturated water content, and weathering degree. The larger in size, the lower in weathering degree, the higher in density, and the lower in porosity and saturated water content. The three fractions of rock fragments, small, medium and large, were 1.9, 2.2 and 2.3 g cm⁻³ in density, 0.16, 0.10 and 0.06 cm³ cm⁻³ in porosity and 8.0%, 4.5% and 3.2% in saturated water content (mass moisture content), respectively. (2) Content of rock fragments was closely related to total bulk density and bulk density of fine earth. With increasing rock fragment content, total bulk density increased while bulk density of fine earth decreased, showing a linear negative relationship. (3) Soil pore distribution was closely related to content of rock fragments. With increasing content of rock fragments, total porosity and capillary porosity of the soil decreased while non-capillary porosity, i.e. macropore, increased. **【Conclusion】** The sum up, rock fragments, especially those small in size, have certain water holding and supplying capacities. In farmlands under water stress, rock fragments can also release some water available for plant growth. The existence of rock fragments in the soil helps improve soil structure and soil water permeability.

Key words Purple soil; Rock fragment; Bulk density; Porosity; Three-Gorge Reservoir Area

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