

露天煤矿区不同粒径土壤组分风蚀的风洞实验*

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摘要: 为探讨露天采矿区人为强烈扰动作用下的土壤风蚀敏感性, 本文采集了准东红沙泉煤矿区周边表层土壤并进行筛分, 开展了风洞模拟实验. 利用风蚀传感器测试了不同粒径土壤组分在不同风速条件下的风蚀量、风沙流结构特性, 并分析了利用风蚀传感器获取的颗粒碰撞数量和能量与风蚀量的对应关系. 结果表明:(1) 随着风速的增加, 不同土壤粒径组分的风蚀速率均显著增加, 但细沙组分的风蚀速率相对较低, 可能与颗粒之间的多种相互作用力有关;(2) 随着高度增加, 输沙量先增加而后呈指数减少, 2 cm或3 cm高度处出现风蚀量峰值, 4 cm之上趋于稳定;(3) 随着风速增加, 颗粒碰撞先增加后减小, 10 m/s的风速是传感器能够感应到颗粒碰撞的临界风速;(4) 风蚀传感器感应的颗粒碰撞能量与实际风蚀量拟合程度较好 ($R^2=0.902$), 实际观测中可用风蚀传感器感应的颗粒碰撞数量和能量来描述土壤风蚀量.

关键词: 土壤风蚀; 土壤粒径; 风洞试验; 露天煤矿

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Wind Tunnel Experiment on Wind Erosion of Different Particle Size Soil Components in Open-Pit Coal Mine

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Abstract: In order to explore the sensitivity of soil to wind erosion under strong human disturbance in open-pit mining area, in this paper, the surface soil around HongShaQuan coal mine area in Zhundong is collected and screened. The wind tunnel simulation experiment is carried out. The wind erosion amount and wind sand flow structure characteristics of different particle size soil components under different wind speed conditions are analyzed by using wind erosion sensor, and the corresponding relationship between the number of particle collision and the amount of wind erosion is analyzed. The results show that: (1) with the increase of wind speed, the wind erosion rates of different soil particle size components increase significantly, but the wind erosion rates of fine sand components are relatively low, which may be related to the interaction between particles; (2) with the increase of height, the sediment transport first increases and then decreases exponentially, and the wind erosion peak appears at the height of 2 cm or 3 cm, and tends to be stable above 4 cm; (3) With the increase of wind speed, the particle collision first increases and then decreases. The wind speed of 10 m / s is the critical wind speed for the sensor to detect the particle collision. The results show that the particle collision energy induced by wind erosion sensor is well fitted with the actual wind erosion amount ($R^2 = 0.902$). In the actual observation, the amount of soil wind erosion can be described by the number and energy of particle collision induced by wind erosion sensor.

Key words: wind erosion of soil; soil particle size; wind tunnel test; open-pit mining areas

0 引言

风力侵蚀作为一种全球环境问题, 在干旱与半干旱地区尤为严重, 其造成的诸如沙尘暴、荒漠化等环境问

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题,严重破坏人类生存环境.因此,风力侵蚀的防治受到各国政府及相关领域学者的高度重视^[1].在防沙治沙的研究中,定量研究不同下垫面的风沙运动规律及风沙流结构是制定合理防治措施的基本前提^[2].土壤自身的颗粒粒径及组成在土壤风蚀过程中起着重要作用^[3-5],风力作用下不同粒径颗粒运动形式不同^[6-9],颗粒碰撞时的能量也有所不同^[10-12],其风沙流结构^[13-19]、输沙量^[20-23]也存在很大差异.因此,作为土壤风蚀过程的一个重要影响因子,近年来土壤机械组成对风蚀的影响一直是学者们关注的热点问题.目前的研究多集中在自然生态系统不同粒径颗粒的可蚀性^[24-27]、风沙流结构^[16,28-30]等方面的差异,而对人为扰动下土壤风蚀敏感性变化的研究较少.

新疆准噶尔盆地东部地区的露天煤炭开采,破坏了地表土壤结构,加之植被覆盖率低,风力作用频繁,土壤抗侵蚀能力较低.本文在准东地区红沙泉露天煤矿周边采集土样,利用中科院新疆生态与地理研究所的莫索湾室内风洞进行试验,研究不同风速条件下、不同粒级土样的风蚀量和风沙流结构,基于风蚀传感器研究颗粒碰撞能量、数量与风蚀量的关系,以为准东矿区的风蚀荒漠化监测和防治提供科学参考.

1 研究材料与方法

1.1 研究区概况

新疆准噶尔盆地东部地区(以下简称准东地区)位于东经 $88^{\circ}30' \sim 90^{\circ}45'$,北纬 $43^{\circ}30' \sim 45^{\circ}30'$,总面积4万平方公里,西部毗邻古尔班通古特沙漠,属温带大陆性气候,全年以西北风为主,多年平均风速为 $2.7 \sim 3.7$ m/s,最大风速达16 m/s,多年平均降水量183.5 mm,蒸发量高达2 042.3 mm;土壤以风沙土和棕漠土为主,养分含量较低;地表植被以荒漠植物为主,盖度约为35%.

1.2 实验设计

在新疆准东红沙泉露天煤矿区($44^{\circ}30'N$; $90^{\circ}20'E$)采集表层土样,将样品带回室内,晒干过筛,筛分成5种粒级的土样(极粗沙 $3 \text{ mm} \sim 1 \text{ mm}$ 、粗沙 $1 \text{ mm} \sim 0.5 \text{ mm}$ 、中沙 $0.5 \text{ mm} \sim 0.25 \text{ mm}$ 、细沙 $0.25 \text{ mm} \sim 0.125 \text{ mm}$ 和极细沙 $<0.125 \text{ mm}$).

多功能环境风洞实验室位于中国科学院新疆生态与地理研究所莫索湾沙漠研究站,风洞全长16.2 m,实验段长8 m,截面宽1.3 m,高1 m,采用侧壁扩散式结构,每侧壁扩散角 2° ,实验风速 $0 \sim 25$ m/s可调.将每个粒级的土样装入长57 cm、宽37 cm和高5 cm的沙盘,并刮平,每个粒级8个重复.由于准东地区风速大多数分布在 $8 \text{ m/s} \sim 14 \text{ m/s}$,因此风洞试验分别设置 8 m/s 、 10 m/s 、 12 m/s 和 14 m/s 四个净风速梯度;吹蚀时间分别设置7 min、10 min、20 min和30 min.每个沙盘实验前后分别用精度为1 g的电子秤称重,以测量净风蚀量.

在沙盘下风向5 cm处平行架设2个垂直点阵式集沙仪(进沙口 $1 \text{ cm} \times 1 \text{ cm}$,高度20 cm),每次吹蚀完毕之后全部取出每个高度处的集沙,用万分之一天平称量,得到风沙流结构.在两集沙仪之间安装1个风蚀传感器(型号Sensit H14-LIN),传感器直径约3 cm,高度约2 cm,用于测量沙尘颗粒撞击数量和撞击动能,每秒记录1次.在集沙仪旁安装1个Met One公司生产的014A风速传感器,用于记录实时风速.具体架设位置如图1所示.实验数据利用Excel2016和Origin2018软件处理.

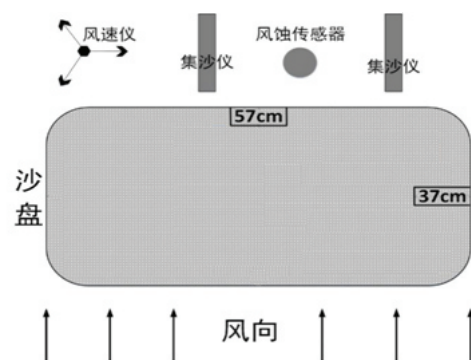


图1 风洞内实验仪器架设位置示意图

Fig 1 Schematic diagram of the installation position of the experimental instrument in the wind tunnel

2 结果与分析

2.1 不同粒径的风速与风蚀量的关系

如图2所示,随风速增加,不同粒径沙盘单位时间的吹蚀量显著增加;风速越大,粒径较小的沙盘吹蚀量越大;同一风速下,极细沙的风蚀率最大,而极粗沙风蚀率最小,细沙风蚀率小于中沙.图3表明风蚀率与颗粒的粒级和风速均存在相关性.如表1所示,各粒级拟合相关系数 R^2 均大于0.8,而粒径小于0.5 mm的三个粒级 R^2 均

大于0.99. 由图4可以看出, 随着粒径降低, 风蚀率整体逐渐增加, 但细沙的风蚀率明显下降. 从理论上讲, 相同风速下, 颗粒粒径越小, 风蚀率越大, 粒径越大, 风蚀率越小, 而本研究与风速理论存在一定偏差, 这可能与粒级的颗粒之间存在多种相互作用力有关(如分子间作用力、电场力等), 颗粒的起动受到约束, 起动风速变大, 相应的吹蚀量就较小.

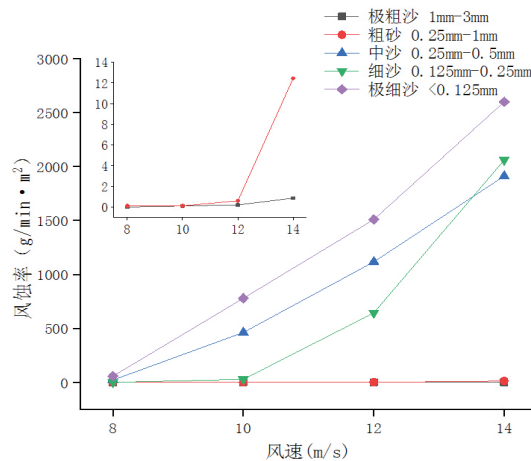


图 2 不同粒级下风蚀率与风速的关系

Fig 2 The relationship between wind erosion rate and wind speed at different particle sizes

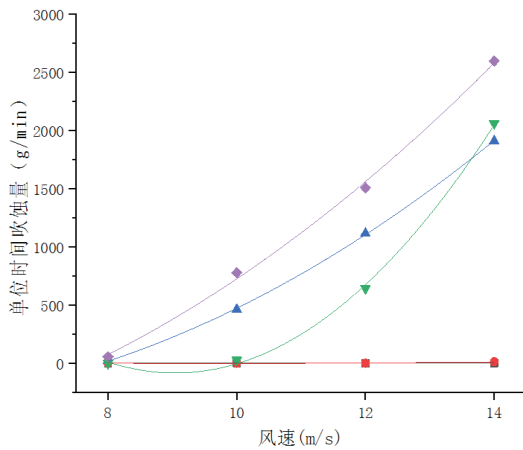


图 3 风速与吹蚀量的拟合曲线

Fig 3 Fitting curve of wind speed and blow erosion

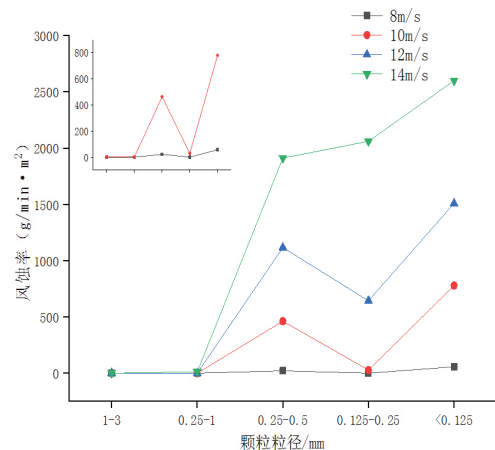


图 4 不同风速下各粒级的风蚀率

Fig 4 Wind erosion rate of each particle size under different wind speeds

表 1 风速与吹蚀量的拟合结果

Tab 1 Fitting results of wind speed and blowing erosion

粒级 (mm)	函数表达式	R^2	P
3~1	$y=0.034 8x^2 -0.632 5x+2.859 3$	0.896 5	<0.01
1~0.5	$y=0.739 7x^2-14.402 2x+68.535 1$	0.841 1	<0.01
0.5~0.25	$y=22.114 6x^2-170.262 5x-35.758 3$	0.999 6	<0.01
0.25~0.125	$y=86.806 3x^2-1 569.919 2x+7 014.531 7$	0.997 6	<0.01
<0.125	$y=23.004 2x^2-88.2 417-692.000 0$	0.994 8	<0.01

2.2 不同风速下各粒级的风沙流结构

如图5所示, 四种风速下, 不同粒级土壤组分颗粒具有不同的风沙流结构, 但基本都是随着高度增加, 输沙量先增加后减少, 输沙量在2 cm、3 cm高度处达到峰值, 在4 cm处急剧下降, 之后趋于稳定; 风蚀物多集中在4 cm高度以内, 占总集沙量的80%. 四种风速条件下, 细沙的风蚀输沙最高, 而极细沙较小. 可能原因是风

速8 m/s时,细沙达到了起动风速,形成跃移质,在风速增大的过程中,跃移质总量逐级增加,风蚀输沙量相应增加.细沙主要在2 cm高度处输沙量达到最大,而极细沙输沙量在3 cm高度处达到最大,之后随着高度增加,输沙量呈指数下降.14 m/s未能达到粗沙的起动风速,故未观测到其输沙量.

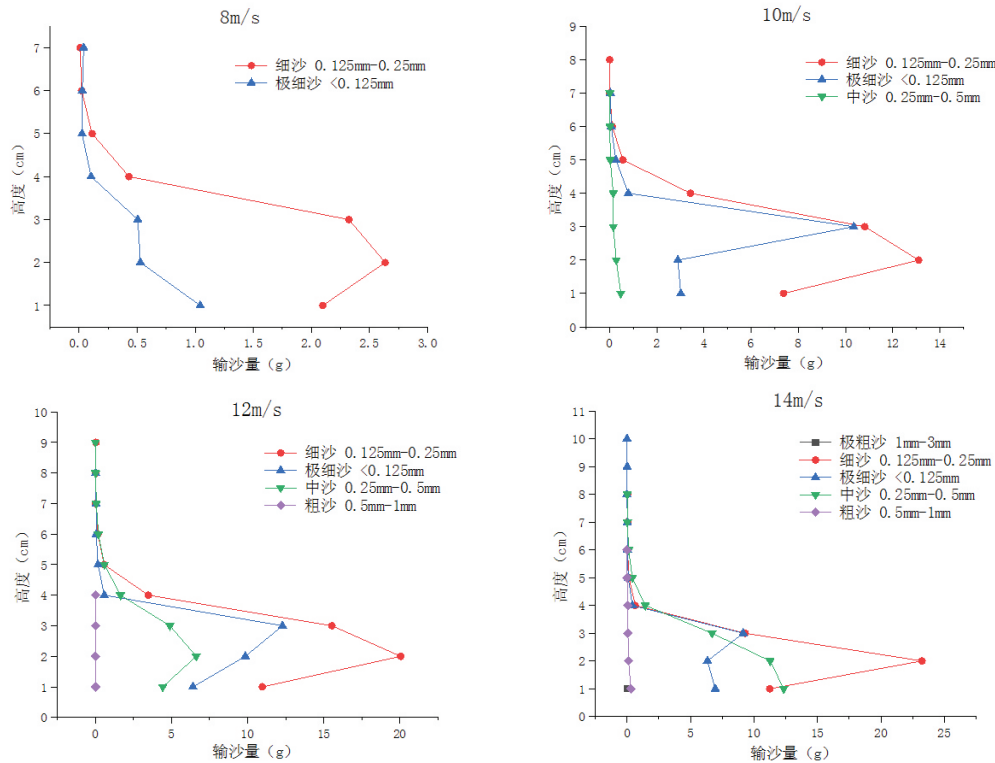


图 5 不同风速条件下风沙流结构

Fig 5 Wind sand flow structure under different wind speed conditions

2.3 不同粒径对颗粒碰撞数量和颗粒碰撞能量的影响

风洞实验中,风蚀传感器每隔一秒计算出颗粒碰撞数量和能量.随着土壤组分粒径的增大,颗粒碰撞数量和能量都不同程度的降低,风蚀传感器能够有效地感应到中沙的颗粒碰撞情况.颗粒碰撞数量和能量与实际风蚀量的拟合相关系数 R^2 分别为0.882和0.902(图6),说明颗粒碰撞能量与实际风蚀量的拟合较好.

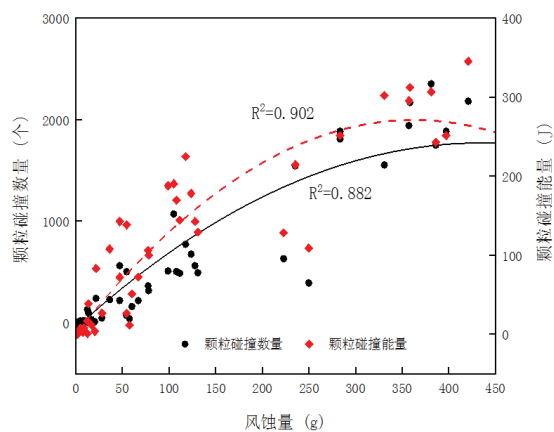


图 6 颗粒碰撞数量和能量与风蚀量的相关关系

Fig 6 The correlation between the number of particle collisions and energy and the amount of wind erosion

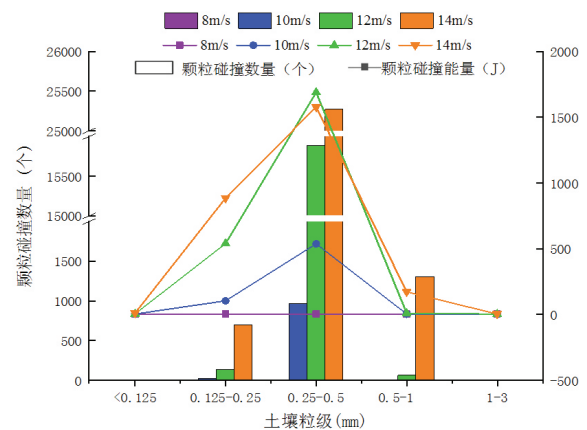


图 7 颗粒碰撞数量和能量随土壤粒级的变化关系

Fig 7 The relationship between the number of particle collisions and energy with soil particle size

如图7所示,但极细沙、极粗沙的颗粒碰撞数量和能量均为0,其原因是该风蚀传感器的精度不足以监测到粒径极小的极细沙,而极粗沙的粒径太大,14 m/s的风速未达到其起动风速,导致这两个粒径范围内的碰撞数量和碰撞能量都为0.

风速为8 m/s时,各粒径范围均未监测到碰撞数量和能量.主要原因是8 m/s只能达到某些小颗粒的起动风速,颗粒越小,传感器就越难以监测得.风速为10 m/s时,细沙、中沙和粗沙的碰撞数量和能量均可以监测得到.可以初步确定,10 m/s的风速是该传感器能够感应到颗粒碰撞能量和数量的临界风速.

3 讨论

风蚀率是判断土壤风蚀潜力和荒漠化敏感性的重要指标.本文通过风洞实验研究发现,在相同风速条件下,土壤粒径越大,单位时间吹蚀量就愈小,这与王仁德^[31,32]等人的观点一致.本研究中细沙的单位时间吹蚀量比中沙小,可能与中沙颗粒之间的相互作用力较大有关,使颗粒不易被风吹蚀.在四种风速条件下,细沙的风蚀量最大,风蚀沙物质在2 cm、3 cm高度处分布最多,在4 cm高度处急剧下降,之后趋于稳定,高度0~4 cm内的风沙流含量超过90%,表明跃移质主要分布在0~4 cm高度范围内,这与前人的研究较一致^[33].

风蚀传感器(型号Sensit H14-LIN)可以计算颗粒碰撞数量与碰撞能量,是风蚀观测的新型设备.随着风速增加,土壤颗粒碰撞数量和能量都不同程度增加.但在本实验中,极粗沙和极细沙的颗粒均未监测到,这可能与传感器的感应碰撞能量范围和颗粒的起动风速有关^[34,35].风速10 m/s时,风蚀传感器能够感应到颗粒碰撞数量和碰撞能量,并对中沙颗粒的碰撞敏感.颗粒碰撞能量与风蚀量的相关性较好($R^2=0.902$),可通过颗粒碰撞数量和能量来描述风蚀量的变化情况.但该风蚀传感器只能较好的描述某个单一粒径范围内(>0.25 mm)的土壤颗粒.因此,利用颗粒碰撞来描述风蚀量既要考虑土壤的机械组成,还要考虑风蚀传感器的感知范围.

4 结论

(1) 随着风速增加,不同粒径土壤组分的风蚀速率显著增加,但细沙的风蚀速率比中沙小,可能与细沙颗粒之间存在多种相互作用力有关.

(2) 风沙流输沙率在2 cm或3 cm高度处达到峰值,4 cm之后趋于稳定,跃移质占90%.

(3) 风蚀传感器能较好的监测中沙颗粒的碰撞情况,随着风速增加,土壤颗粒的碰撞情况呈现规律性的变化,10 m/s的风速是该传感器能够感应到颗粒碰撞能量和数量的临界风速;颗粒碰撞能量与风蚀量的相关性较好($R^2=0.902$),可通过颗粒碰撞数量和能量来描述风蚀量的变化情况.

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