

蚯蚓仿生注液沃土装置设计与试验

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摘要:蚯蚓吞噬土壤, 构建洞穴, 发挥了肥沃土壤的重要作用。该文借助工程仿生技术手段, 运用计算机图像处理技术对蚯蚓头部、体节轮廓图像进行量化分析, 提取并拟合蚯蚓头部和体节的轮廓曲线, 构建注液沃土装置的仿生几何结构表面。仿蚯蚓背孔排布方式设计了3孔和6孔注液型沃土装置, 以UHMWPE为材料制备样机, 并采用农机土槽试验系统开展注液沃土装置样机选型试验, 考察孔数、是否注液、材料、表面结构4个参数对工作阻力和土壤粘附量的影响。试验结果表明, 各参数对工作阻力的影响程度依次为: 注液>孔数>材料>表面结构; 对土壤粘附量的影响程度依次为: 表面结构>孔数>材料>注液。从8类样机中确定的优选类型为: 有6个注液孔、UHMWPE材质且具有仿生几何结构表面的仿生注液沃土装置。对选定的样机进行验证, 结果表明: 在相同试验条件下, 该样机的平均工作阻力为283.48 N, 平均土壤粘附量值为10.93 g, 均低于其他类型样机。该研究工作可为实施机械化沃土工程提供技术参考。

关键词:仿生; 设计; 几何结构表面; 脱附减阻; 注液沃土; 蚯蚓

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0 引言

利用农机具改变耕层土壤地貌, 人为创造土壤洞道, 改善耕层土壤结构, 可以达到蓄水保墒、减少水土流失和风沙扬尘的目的。仿生注液沃土的技术思路是通过学习土壤动物改变耕层土壤性状的方式, 构建土壤洞道并施加液体肥, 从而提高土壤肥力, 促进作物根系生长^[1-2]。依据该技术思路设计的沃土装置, 通过挤压土壤形成洞道或裂隙, 调节土壤孔隙度, 控制耕层水分^[3-6], 并采用注射液体肥的方式增加耕层含水率和养分含量^[7-9]。仿生注液沃土技术改善了耕层土壤的理化性状, 为土壤动物生存、农作物生长创造有利的生态环境^[10-13]。

亿万年来, 蚯蚓进化出优异的生存本能, 适应、改造了土壤环境, 具有精巧的生物形态^[14-15]。蚯蚓在土壤中

运动, 背孔不断分泌出黏性体液, 溶解大量的氧气, 并顺着节间沟浸润体表, 形成液体保护膜^[16-17]。蚯蚓在耕层土壤中构建洞穴而不粘附土粒, 体表粘液的作用不可忽视^[18-19]。蚯蚓脱附减阻的机理在于, 蚯蚓在构建洞道过程中, 体表粘液形成润滑层, 减小了蚯蚓运动的阻力^[20]。并且, 蚯蚓的环节结构减小了体表与土壤的接触面积, 破坏了界面水膜的连续性, 降低了土壤对体表的粘附力, 表现出良好的减阻性能^[21-23]。将蚯蚓在土壤中运动的脱附减阻特性应用于注液沃土工作部件, 对减小土壤与部件之间的粘附具有积极意义^[24-26]。

本研究从蚯蚓运动、黏液分泌和体表结构耦合形成的优异减阻性能获得启示, 借助工程仿生技术手段和方法^[27-35], 仿照蚯蚓构建洞穴改良土壤的生存方式, 设计仿生注液沃土装置, 期望达到改善土壤结构, 增加耕层肥力的目的。在此基础上, 以最小工作阻力和土壤粘附量为优化目标, 在保证所要求的土壤洞道或液体沃土质量前提下, 优选仿生注液沃土装置样机类型, 分析前进速度、入土深度、注液量与装置土壤粘附量、工作阻力之间的关系, 求解仿生注液沃土装置最优工作参数, 提高装置工作过程的脱附减阻性能。

1 材料与方法

注液沃土机具主要由深松铲和仿生注液沃土装置2

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部分组成,工作原理为:在拖拉机牵引下,前置深松铲在地表开具有一定深度的沟槽,注液沃土装置的锥形轮廓挤压、分离土壤,肥箱中的液体肥在压力作用下进入装置内部,并由注液孔不断流出充盈装置环槽,浸润部件表面,渗入耕层土壤,如图1所示。注液沃土装置随拖拉机牵引向前运动,一方面在耕层土壤洞道内施加液体肥,另一方面液体肥与装置的环状结构相配合,在装置外表面与土壤之间不断形成水膜,降低仿生注液沃土装置与土壤之间的黏附力和摩擦阻力。

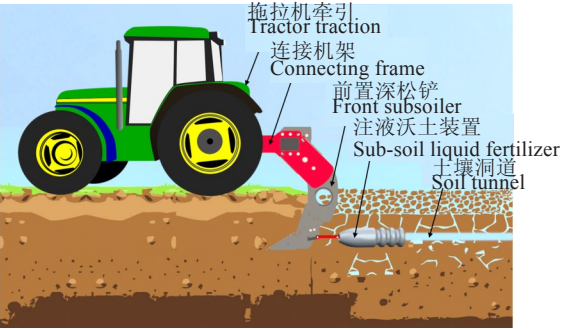
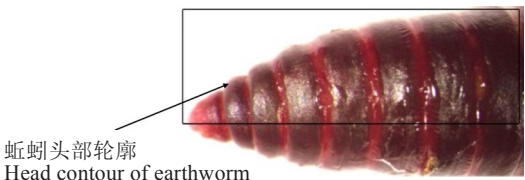


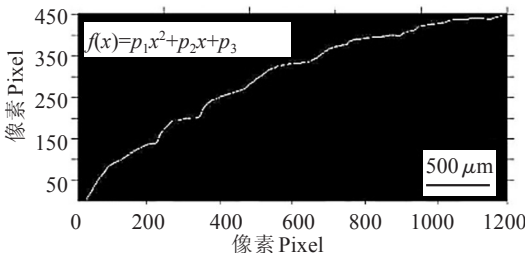
图1 注液沃土机具工作示意图
Fig.1 Schematic diagram of sub-soil liquid fertilizer

1.1 蚯蚓体表结构轮廓曲线的提取

本文以赤子爱胜蚓(*Eisenia foetida*)为仿生对象。该类蚯蚓为广布品种,体长50~60 mm,体宽3~5 mm,体节数在90~110节之间,体呈暗红色。使用体视显微镜观察并拍摄其分泌体液时的体表特征照片,采用数学分析软件Matlab 2013,从体视显微镜图片中检测并提取蚯蚓体表外缘轮廓。蚯蚓头部(图2a)是运动时首先接触并侵入土壤的部位,其外缘轮廓可作为注液沃土装置外部曲线,提取蚯蚓头部几何结构表面的轮廓曲线,如图2b所示。轮廓曲线方程的拟合优度是保证设计精度和加工难易度的重要环节,精度过低,曲面结构设计不可靠;精度过高,又会增加样机的加工难度。经比较,本文选用二次多项式函数作为蚯蚓头部轮廓曲线的拟合方程,如式(1)所示。



a. 蚯蚓头部
a. Earthworm head



b. 蚯蚓头部轮廓曲线
b. Earthworm head contour curve

图2 蚯蚓头部及其轮廓曲线
Fig.2 Earthworm head and its contour curve

$$f(x)=p_1x^2+p_2x+p_3 \tag{1}$$

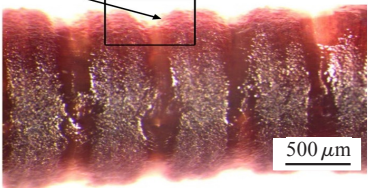
式中 p_1 的取值范围为-0.005~-0.003, p_2 的取值范围为0.8至0.9,参数 p_3 的取值范围为1.2~1.5,拟合优度 R^2 为0.99,标准误差RMSE为0.79。

蚯蚓体节的几何结构(图3a)降低了体表与土壤的接触面积,峰谷交错的节间沟波纹结构破坏了体表与土壤之间水膜的连续性,降低了土壤黏附阻力,该结构可作为注液部件的表面轮廓。蚯蚓体节几何结构轮廓曲线(图3b)的拟合方程为傅里叶级数方程,如式(2)所示。

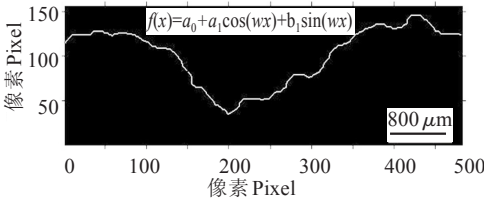
$$f(x)=a_0+a_1\cos(wx)+b_1\sin(wx) \tag{2}$$

式中 a_0 的取值范围为6.0~6.2,参数 a_1 的取值范围为2.3~2.5,参数 b_1 的取值范围为1.5~1.8,参数 w 的取值范围为0.25~0.27,拟合优度 R^2 为0.95,标准误差RMSE为0.48。

蚯蚓体节几何结构
Geometrical structure of earthworm segments



a. 蚯蚓体节
a. Segments of earthworm



b. 蚯蚓体节轮廓曲线
b. Contour curve on segments of earthworm

图3 蚯蚓体节几何结构轮廓曲线

Fig.3 Contour curve of earthworm segment geometry

1.2 注液沃土装置仿生结构参数设计

通过对蚯蚓头部、体节几何结构特征进行量化分析,根据外缘轮廓的几何特征曲线构建仿生注液沃土装置的几何结构表面。注液沃土装置由仿照蚯蚓头部轮廓曲线设计的锥形触土部件和仿照蚯蚓体节特征曲线设计的带有几何结构表面的管状注液部件组成。注液部件表面峰谷交错,仿蚯蚓背孔排布方式,在波谷内设计3个斜向防堵塞注液孔。为提高注液的均匀性,在3孔注液部件的基础上,改进设计双侧6孔型注液部件。采用参数化建模软件Creo 2.0(PTC Corporate Headquarters, Needham, USA)构建的注液沃土装置3D结构如图4所示。

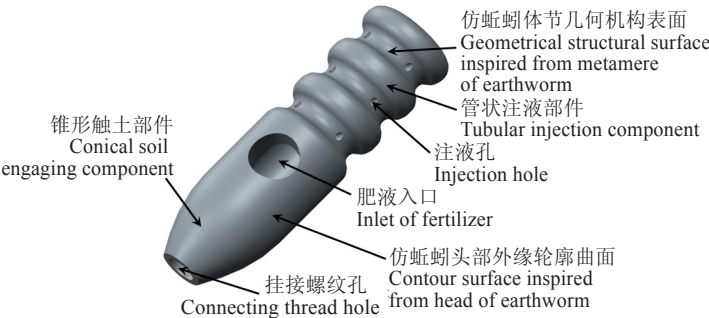


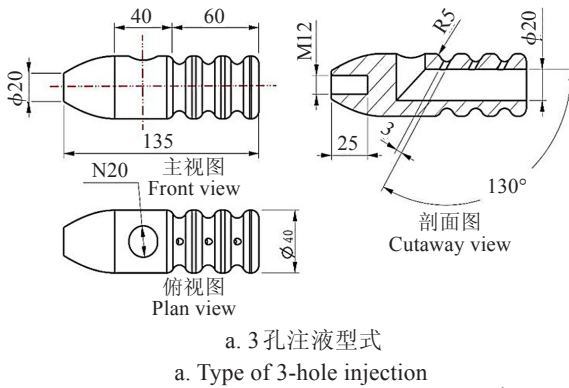
图4 仿生注液沃土装置结构

Fig. 4 Structure of bionic sub-soil liquid fertilizer

与蚯蚓洞道类似,草原上的鼠洞同样具有蓄水和排水的作用。鼠洞裂隙内含有一定水分,可以保持洞内湿润;鼠洞群地下排布纵横交错,有利于及时排空降水,保持鼠洞结构^[36-37]。有研究者调查了草原田鼠(*Microtus pennsylvanicus*)的鼠洞尺寸^[1],本文参考鼠洞直径设计注液沃土装置的结构尺寸,将外径设定为40 mm,内径设定为20 mm,装置长度设定为135 mm。锥形触土部件起到挤压、分离土壤的作用,轮廓曲线方程如式(3)所示。

$$y=-0.004x^2+0.85x+1.35 \tag{3}$$

式中 x 的取值范围为 25~60 mm。



装置在土层中运动时,管状注液部件的几何结构表面起到脱附减阻的作用,设定管状部件上有3个注液环槽,轮廓曲线方程如式(4)所示。

$$y=6.15+2.4\cos(0.26x)+1.67\sin(0.26x) \tag{4}$$

式中 x 的取值范围为 5~25 mm。

液体肥入口、注液孔与管状部件内径分别连通,采用计算流体力学方法仿真计算注液沃土装置内部流场的出口压力和各出口速度矢量^[1]。依据出口压力大提高注液孔防堵性能、各出口流速均匀有助于液体肥料均匀喷施的原则,设计的仿生注液沃土装置尺寸参数如图5所示。

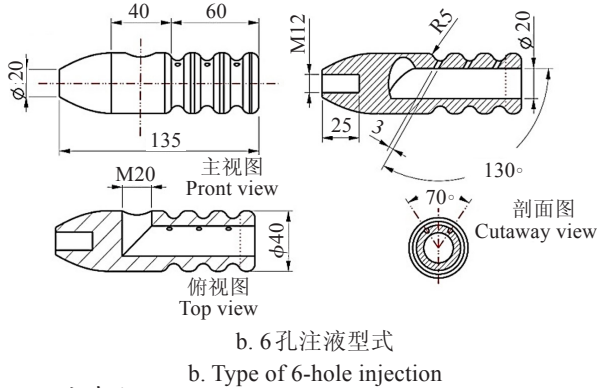


图5 仿生注液沃土装置尺寸参数

Fig.5 Dimension parameters of bionic sub-soil liquid fertilizer

1.3 注液沃土装置材质及配套深松铲

超高分子量聚乙烯(UHMWPE)具有耐磨损、耐腐蚀和表面疏水等优异性能,可降低土壤粘附量,并减小肥液流动时装置内壁产生的能量损失。选用密度为0.95 g/cm³、摩擦系数为0.17、吸水性为0.01%的UHMWPE作为注液沃土装置的加工材料,进一步减小土壤对装置的粘附,降低工作阻力。

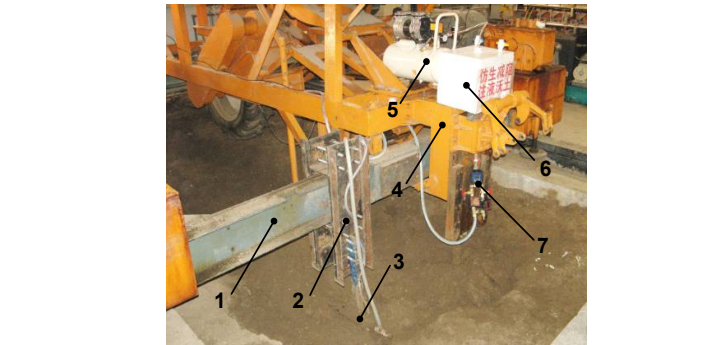
作业过程中,为避免注液沃土装置锥形触土部件承受过高的工作阻力,选择课题组前期研制的仿生深松铲作为配套机具。该深松铲采用了仿照穿山甲鳞片外表面设计的棱纹形深松铲刃,以及仿照小家鼠爪趾纵剖面轮廓线设计的指数曲线型深松铲柄,其中铲刃间隙角为4°,铲柄宽60 mm,厚30 mm^[38]。

1.4 土槽试验

采用吉林大学生物与农业工程学院农业机械实验室的土槽台车试验系统进行仿生注液沃土装置样机测试。通过控制土槽台车的速度和仿生注液沃土装置的工作参数,以仿生注液沃土装置的土壤粘附量、工作阻力为考核指标,共进行8类样机的对比试验,遴选出土壤粘附量和工作阻力较小的样机类型。根据试验优化设计原理,分析前进速度、入土深度、注液量与仿生注液沃土装置土壤黏附量、工作阻力之间的关系,优化装置的工作参数。

土槽试验系统由土壤、台车、数据采集3个子系统组成,如图6所示。土槽长45 m,宽2.8 m,土壤深度1.8 m,土壤物理特性参数如表1所示。土槽两边铺设导轨,台车系统在导轨上运行。土槽台车主要由机架、行走、动力和控制等部分组成。

拉压力传感器两端分别连接深松铲与仿生注液沃土装置,可以有效测定仿生注液沃土装置的工作阻力。机



1. 台车横梁 2. 连接机架 3. 试验样件 4. 活动台架 5. 空气压缩机 6. 肥液箱 7. 数字流量计
1. Trolley crossbeam 2. Connecting rack 3. Test sample 4. Movable rack 5. Air compressor 6. Fertilizer tank 7. Digital flowmeter

图6 土槽试验系统

Fig.6 Soil bin testing system

表1 试验土壤物理特性参数

Table 1 Soil physical property parameters

参数 Parameter	值 Value
容重 Volume weight $\rho / \text{mg} \cdot \text{m}^{-3}$	1.79
杨氏模量 Young's modulus E / MPa	1.14
泊松比 Poisson's ratio ν	0.30
土壤坚硬度 Soil hardness /kPa	1341.30
含水率 Moisture content $K / \%$	20.03

具的注液系统安装在土槽台车的活动台架上,可在台车横梁上左右移动。注液系统由空气压缩机(0.7 MPa,台州,中国)、肥液箱(聚丙烯材质,自制)、数字式液体涡轮流量计(K24型,温州永嘉,中国)组成。空气压缩机开启后,用调压阀调节气压,将肥液箱中的液体肥输送至装置内部,通过数字流量计读取液体的质量、流量,采用快速开关阀门开启和关闭注液功能,实现对装置注液过程的控制。土槽台车通过机架连接并牵引深松铲和仿生注液

沃土装置运动。在土槽台车牵引行进过程中,数据采集系统记录仿生注液沃土装置的工作阻力;台车停止后关闭注液系统,采用称质量法测定仿生注液沃土装置的土壤粘附量。

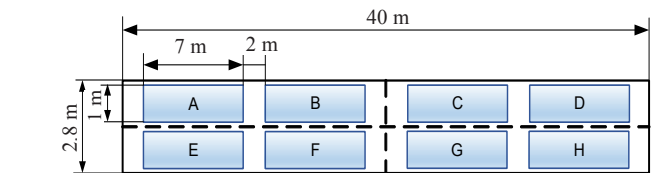
1.4.1 工作阻力及土壤粘附量测试方法

注液沃土装置与仿生深松铲通过全桥式应变传感器(H3-C3-6B 750 kg, ZEMIC, China)连接。在土槽车牵引样机运动过程中,传感器将拉力信号传递至应变式传感器信号放大器(RW-ST01A, SMOWO, China)。经放大器调理后,拉力信号由数据采集卡(myDAQ, National Instruments, USA)传送至计算机。基于 LabVIEW 2014 (National Instruments, USA)虚拟仪器平台设计了工作阻力数据采集程序。程序设定采样频率为 100 Hz,经拉力—电压标定曲线换算得到工作阻力,并调用虚拟示波器显示。所有采样值经输出模块存储为文本文件后,完成对工作阻力的数据采集过程。在进行工作阻力测试前,需要对拉力传感器进行标定。传感器与数据采集系统相连通,通过万能试验机均匀加载拉力,由数据采集卡的测试面板读取并记录电压值,标定完成后可以得到拉力—电压之间对应的关系曲线。将标定数据输入至 LabVIEW 2014 参数管理模块 MAX Automation Explorer,采集程序通过电压信号计算实际工作阻力。

在装置到达出土调整区之后,关闭注液系统,采用称质量法测量装置的土壤粘附量。称量时,用毛刷剥离粘附在注液沃土装置上的土壤,收集于密封袋之中,然后立即用电子天平称量土壤质量。

1.4.2 试验区划分

试验准备阶段在土槽内撒少量水并翻整土壤,深度达到 40 cm;之后镇压土壤,确保地表平整均匀;多点测量土槽测试区内土壤的含水率和坚实度,误差分别控制在 5% 和 10% 以内,确保土壤物理条件的一致性。由于注液沃土装置工作后会改变土壤物理参数,为保证试验准确性,需要分区安排,整地一次后可以完成一组完整的试验。试验区划分如图 7 所示:在土槽中选择 40 m 作为试验区,分为 A-H 测试区,每个测试区长 7 m,宽 1 m。为获得土槽台车稳定的前进速度,在测试区前后分别设置了入土和出土调整区各 2 m,仅对台车进入测试区后的数据进行采集并作为测定值。全部试验完成之后,重复翻整、晾晒、镇压土槽测试区内的土壤,在试验前测量土壤的含水率和坚实度,在规定的误差范围内重复测试 3 次,取平均值作为最终测试结果。



注:A~H表示试验区
Note: A-H are testing plots.

图 7 土槽试验区划分
Fig.7 Division of soil bin testing plots

1.5 样机类型及试验方案

为了验证仿生注液沃土装置的减黏膜脱附效果,依次在深松铲后安装 8 种类型的样机,如表 2 所示。

表 2 注液沃土装置类型
Table 2 Type of sub-soil liquid fertilizer

编号 No.	材质 Material	结构类型 Structural types
1	铸铁 Cast iron	无表面结构,3 孔
3		有表面结构,3 孔
5		无表面结构,6 孔
7	超高分子量聚乙烯 UHMWPE	有表面结构,6 孔
2		无表面结构,3 孔
4		有表面结构,3 孔
6		无表面结构,6 孔
8		有表面结构,6 孔

根据玉米种植农艺条件(株距 30 cm,行距 65 cm),在田间 1 m 长的玉米垄内可种植 4 株玉米。以单株玉米生长期至少施加 50~100 g 肥液,注液沃土装置运行速度 1 m/s 计算,田间 1 m 长的玉米垄内需要施加 200~400 g 肥液。因此以质量流量 200 g/s 作为入口的边界条件,在土槽试验台车牵引速度 1.0 m/s、样机入土深度 15 cm、注液量 200 g/s 的工作条件下,进行装置工作阻力和土壤粘附量的测试。

以有无表面结构、孔数、材料和是否注液作为装置性能的试验因素,以工作阻力和土壤粘附量作为考核指标,每个因素取 2 个水平,选用正交试验表 $L_8(2^4)$,正交试验因素和水平如表 3 所示。每组试验重复 3 次,分别记录测试结果。采用极差分析和方差分析方法,选择出最优的样机类型,并通过分析测试结果极差值的大小确定出各因素的主次和最优水平,找到各因素的最优水平组合。

表 3 正交试验因素水平表
Table 3 Factor level table of orthogonal test

水平 Levels	试验因素 Factors			
	A	B	C	D
1	无	3 孔	铸铁	注液
2	有	6 孔	UHMWPE	不注液

注:A 表示表面结构;B 表示孔数;C 表示材料类型;D 表示注液方式。下同。
Note: A is surface structure; B is hole number; C is material type; D is injection mode. The same below

2 结果与分析

2.1 正交表分析

正交试验方案和极差分析结果如表 4 所示。由极差分析结果可知,影响工作阻力的试验因素为:注液(D)>孔数(B)>材料(C)>表面结构(A),各因素的优水平分别为注液(D_1)、6 孔(B_2)、UHMWPE(C_2)和有表面结构(A_2),即获得最小工作阻力的最优组合为: $D_1B_2C_2A_2$ 。影响土壤粘附量的试验因素为:表面结构(A)>孔数(B)>材料(C)>注液(D),各因素的优水平分别为有表面结构(A_2)、6 孔(B_2)、UHMWPE(C_2)、注液(D_1),即获得最小土壤粘附量的最优组合为 $A_2B_2C_2D_1$ 。

2.2 方差分析

方差分析结果(显著性水平 $P<0.05$)如表5所示。由表4和表5可知,有无表面结构对注液沃土装置工作阻力的影响显著,对土壤粘附量的影响极显著,表明具有表面结构的样机可降低工作阻力及土壤粘附量。孔数对工作阻力的影响显著,工作阻力随着孔数的增加而

减小;孔数对土壤粘附量的影响极显著,6孔注液型可显著减小土壤粘附量。材料对工作阻力及土壤粘附量的影响均显著,采用UHMWP时,工作阻力和土壤粘附量均达到最小值。有无注液对工作阻力和土壤粘附量的影响均极显著,在注液的情况下,工作阻力和土壤粘附量均有效降低。

表4 正交试验设计表及极差分析
Table 4 Orthogonal test design table and range analysis

编号 No.		A	B	C	D	工作阻力 Working resistance /N	土壤粘附量 Adhesion amount of soil /g
1		1	1	1	1	562.29	72.01
2		1	1	1	2	590.64	98.24
3		1	2	2	1	411.83	23.72
4		1	2	2	2	401.10	59.39
5		2	1	2	1	349.07	12.44
6		2	1	2	2	720.88	28.19
7		2	2	1	1	308.11	15.99
8		2	2	1	2	551.78	19.42
工作阻力 Working resistance /N	K_1	1 965.86	2 222.88	2 012.82	1 631.3	主次因素: D、B、C、A	
	K_2	1 929.84	1 672.82	1 882.88	2 264.4	优水平: D_1 、 B_2 、 C_2 、 A_2	
	R	36.02	550.06	129.94	633.1	最优组合: $D_1B_2C_2A_2$	
土壤粘附量 Adhesion amount of soil /g	K_1	253.36	210.88	205.66	124.16	主次因素: A、B、C、D	
	K_2	76.04	118.52	123.74	205.24	Primary and secondary factors: A, B, C, D	
	R	177.32	92.36	81.92	81.08	优水平: A_2 、 B_2 、 C_2 、 D_1	
						Optimal levels: A_2 , B_2 , C_2 , D_1	
						最优组合: $A_2B_1C_2D_1$	
						Optimal combination: $A_2B_2C_2D_1$	

表5 试验结果方差分析
Table 5 Analysis of variance of test results

指标 Index	方差来源 Source of variance	SS	df	MS	F	P
工作阻力 Working resistance/N	A	29 949.78	1	29 949.78	4.51	0.047 *
	B	56 791.25	1	56 791.25	8.25	0.022 *
	C	30 560.63	1	30 560.63	4.59	0.045 *
	D	79 868.34	1	79 868.34	11.99	0.003 **
	误差 Error	206 545.94	19	6 660.31		
	总计 Total	5 200 860.70	24			
土壤粘附量 Adhesion amount of soil	A	11 940.31	1	11 940.31	89.74	<0.0001 **
	B	3 275.07	1	3 275.07	24.61	<0.0001 **
	C	2 561.01	1	2 561.01	19.25	<0.0001 **
	D	2421.65	1	2 421.65	18.20	<0.0001 **
	误差 Error	2 528.07	19	133.06		
	总计 Total	63 844.59	24			

注:SS表示平方和,df表示自由度,MS表示均方和,*表示该项显著($P<0.05$),**表示该项极显著($P<0.01$)。
Note: SS is sum of squares; df is degree of freedom; MS is mean squares; *shows this term is significant ($P<0.05$); ** shows this term is very significant ($P<0.01$).

通过对比分析,以工作阻力为指标得到的最优组合为 $D_1B_2C_2A_2$,其中注液(D)对工作阻力的影响最显著。以土壤粘附量为指标得到的最优组合为 $A_2B_2C_2D_1$,4个因素与土壤粘附量呈极显著相关,由F值可知,最显著的因素为表面结构(A)。通过综合分析,得到最优组合为 $A_2B_2C_2D_1$;优选的样机类型为:含有6个注液孔、UHM-WPE材质且具有几何结构表面的仿生注液沃土装置(8号样机)。

为确认样机类型分析结果的有效性,在土槽试验台车牵引速度1.0 m/s、样机入土深度15 cm、注液量200 g/s的工作条件下,对优选的样机进行土槽验证试验并重复3次,试验结果如图8所示。

测试结果表明,工作阻力、土壤粘附量与样机的材质和结构类型密切相关,工作阻力和土壤粘附量随着选用UHMWPE材质、增加孔数、构建表面结构呈逐步降低趋

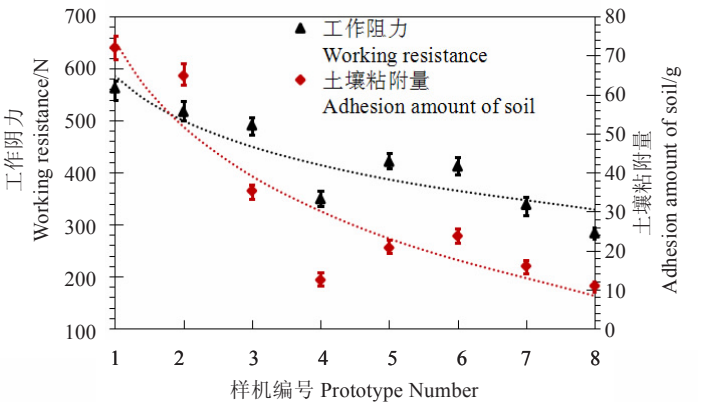


图8 土槽试验结果
Fig.8 Soil bin test results

势。其中,注液沃土装置8号样机的工作阻力平均值为283.48 N,土壤粘附量平均值为10.93 g,显著低于其他样机测试结果,与样机类型分析结果一致。

3 结论

本研究通过学习蚯蚓粘液的分泌过程,采用仿生设计方法设计了注液沃土装置。采用土槽台车试验系统进行了仿生注液沃土装置样机选型和工作参数试验。以土壤粘附量、工作阻力为试验指标,考察了装置的表面结构、注液孔数量、材质和注液方式4个性能参数对目标值的影响,从8类样机遴选出土壤粘附量和工作阻力较小的样机类型,得到如下结论:

1)性能参数对样机工作阻力的影响程度为:注液>孔数>材料>表面结构,各试验因素的优水平分别为注液、6孔、UHMWPE和有表面结构。性能参数对土壤粘附量的影响程度为:表面结构>孔数>材料>注液,各因素的优水平分别为有表面结构、6孔、UHMWPE和注液;

2)有无表面结构对注液沃土装置工作阻力的影响显著,对土壤粘附量的影响极显著。具有表面结构的样机可降低工作阻力,减小土壤粘附量。孔数对工作阻力的影响显著,工作阻力随着孔数的增加而减小;孔数对土壤粘附量的影响极显著,6孔注液型可显著减小土壤粘附量。材料对工作阻力及土壤粘附量的影响均显著,采用UHMWP时,工作阻力和土壤粘附量均达到最小值。有无注液对工作阻力和土壤粘附量的影响均极显著,在注液的情况下,工作阻力和土壤粘附量均有效降低;

3)通过综合分析,从8类样机中确定的优选类型为:具有表面几何结构的6孔注液型UHMWPE材质沃土装置。验证试验表明:在相同试验条件下,该样机工作阻力的平均值为283.48 N,土壤粘附量平均值为10.93 g。低于其他类型样机的测试结果,可显著减小土壤粘附量,降低工作阻力。

[参考文献]

- [1] 张东光. 蚯蚓粘液脱附减阻机理和仿生沃土应用[D]. 长春: 吉林大学, 2016.
Zhang Dongguang. Resistance Reduction Mechanism of Earthworm Mucus Desorption and Application of Biomimetic Fertile Soil[D]. Changchun: Jilin University, 2016. (in Chinese with English abstract)
- [2] 张东光, 吴亚丽, 黄高鉴, 等. 一种具有蚯蚓条播功能的沃土装置: 10141252.X[P]. 2017-06-30.
- [3] Tuohy P, Humphreys J, Holden N M, et al. Visual drainage assessment: A standardised visual soil assessment method for use in land drainage design in Ireland[J]. Irish Journal of Agricultural and Food Research. 2016, 55(1): 24—35.
- [4] Valbuena Parralejo N, Fenton O, Tuohy P, et al. Phosphorus and nitrogen losses from temperate permanent grassland on clay-loam soil after the installation of artificial mole and gravel mole drainage[J]. Science of the Total Environment, 2019, 659(2): 1428—1436.
- [5] Tuohy P, Humphreys J, Holden N M, et al. Runoff and subsurface drain response from mole and gravel mole drainage across episodic rainfall events[J]. Agricultural Water Management, 2016, 169(1): 129—39
- [6] Dhakad S S, Rao K V R, Mishra K P, et al. Effect of mole drain

spacing and depths on the growth character and yield of soybean in vertisols of MP[J]. International Journal of Agricultural Engineering, 2013, 6(1): 173—176.

- [7] 王金武, 周文琪, 白海超, 等. 液肥深施肥差动式双向供肥分配装置设计与试验[J]. 农业机械学报, 2018, 49(6): 105—111.
Wang Jinwu, Zhou Wenqi, Bai Haichao, et al. Design and test of differential two-way fertilizer distribution device for liquid fertilizer deep applicator[J]. Transactions of the Chinese Society for Agricultural Machinery, 2018, 49(6): 105—111. (in Chinese with English abstract)
- [8] 王金武, 潘振伟, 杨欣伦, 等. 深施肥液态施肥机液肥转子式转换器设计与试验[J]. 农业机械学报, 2014, 45(10): 110—115, 65.
Wang Jinwu, Pan Zhenwei, Yang Xinlun, et al. Design and test of liquid fertilizer rotor converter for DEEP-APPLICATION liquid fertilizer applicator[J]. Transactions of the Chinese Society for Agricultural Machinery, 2014, 45(10): 110—115, 65. (in Chinese with English abstract)
- [9] 刘春香, 王金武, 周文琪, 等. 液肥深施双斜孔式喷肥针动力学分析与试验[J]. 农业机械学报, 2016, 47(3): 53—58.
Liu Chunxiang, Wang Jinwu, Zhou Wenqi, et al. Kinetic analysis and experiment of double oblique hole spraying needle for liquid fertilizer deep application[J]. Transactions of the Chinese Society for Agricultural Machinery, 2016, 47(3): 53—58. (in Chinese with English abstract)
- [10] Dixit J, Mahal J, Manes G. Design of nitrogen (liquid urea) metering mechanism for point injection in straw mulched fields[J]. AMA-Agricultural Mechanization in Asia Africa and Latin America, 2016, 47(3): 28—35.
- [11] Liu Hongli, Wang Xi, Bingkun Jin. Study on NDVI optimization of corn variable fertilizer applicator[J]. Inmateh-Agricultural Engineering, 2018, 56(3): 193—202.
- [12] Zhang Chunfeng, Wang Xiu, Li Jinpeng, et al. Development and experiments on the injection system of the self-propelled liquid fertilizer machine [C]. 5th Annual IEEE International Conference on Cyber Technology in Automation: Control and Intelligent Systems. IEEE, 2015: 1650—1654.
- [13] 王金武, 纪文义, 冯金龙, 等. 液态施肥机的设计与试验研究[J]. 农业工程学报, 2008, 24(6): 157—159.
Wang Jinwu, Ji Wenyi, Feng Jinlong, et al. Design and experimental investigation of the liquid fertilizer applicator[J]. Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), 2008, 24(6): 157—159. (in Chinese with English abstract)
- [14] Blouin M, Hodson M E, Delgado E A, et al. A review of earthworm impact on soil function and ecosystem services[J]. European Journal of Soil Science, 2013, 64(2): 161—182.
- [15] Barré P, Mckenzie B, Hallett P. Earthworms bring compacted and loose soil to a similar mechanical state[J]. Soil Biology and Biochemistry, 2009, 41(3): 656—658.
- [16] Gu Yunqing, Fan Tianxing, Mou Jiegang, et al. A review of bionic technology for drag reduction based on analysis of abilities the earthworm[J]. International Journal of Engineering Research in Africa, 2015, 19: 103—111.
- [17] Jia Honglei, Wang Wenjun, Wang Wanpeng, et al. Application of anti-adhesion structure based on earthworm motion characteristics [J]. Soil and Tillage Research, 2018, 178: 159—166.

- [18] Ren Luquan, Cong Qian, Tong Jin, et al. Reducing adhesion of soil against loading shovel using bionic electro-osmosis method [J]. *Journal of Terramechanics*, 2001, 38(4): 211—219.
- [19] Ren Luquan. Progress in the bionic study on anti-adhesion and resistance reduction of terrain machines[J]. *Science in China Series E: Technological Sciences*, 2009, 52(2): 273—284.
- [20] Zhang Dongguang, Chen Yuxiang, Ma Yunhai, et al. Earthworm epidermal mucus: Rheological behavior reveals drag-reducing characteristics in soil[J]. *Soil and Tillage Research*, 2016, 158: 57—66.
- [21] Zu Y Q, Yan Y Y. Numerical simulation of electroosmotic flow near earthworm surface[J]. *Journal of Bionic Engineering*, 2006, 3(4): 179—186.
- [22] Zhang Rui, Chen Bin, Li Jianqiao, et al. DEM simulation of clod crushing by bionic bulldozing plate[J]. *Journal of Bionic Engineering*, 2008, 5(1): 72—78.
- [23] Li Jianqiao, Kou Bingxue, Liu Guomin, et al. Resistance reduction by bionic coupling of the earthworm lubrication function[J]. *Science China Technological Sciences*, 2010, 53(11): 2989—2995.
- [24] Song C W, Lee D J, Lee S Y. Bioinspired segment robot with earthworm-like plane locomotion[J]. *Journal of Bionic Engineering*, 2016, 13(2): 292—302.
- [25] 贾洪雷, 郑健, 赵佳乐, 等. 仿蚯蚓运动多功能开沟器设计及参数优化[J]. *农业工程学报*, 2018, 34(12): 62—71.
Jia Honglei, Zheng Jian, Zhao Jiale, et al. Design and parameter optimization of multi-function trencher imitating earthworm motion[J]. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 2018, 34(12): 62—71. (in Chinese with English abstract)
- [26] 谷云庆, 牟介刚, 代东顺, 等. 基于蚯蚓背孔射流的仿生射流表面减阻性能研究[J]. *物理学报*, 2015, 64(2): 310—319.
Gu Yunqing, Mou Jiegang, Dai Dongshun, et al. Surface drag reduction performance of bionic jet based on earthworm back hole jet[J]. *Journal of Physics*, 2015, 64(2): 310—319. (in Chinese with English abstract)
- [27] 张锐, 乔钰, 吉巧丽, 等. 驯鹿足底非规则特征形貌数学模型构建及验证[J]. *农业工程学报*, 2017, 33(8): 56—61.
Zhang Rui, Qiao Yu, Ji Qiaoli, et al. Establishment and validation of mathematical models for irregular morphology of reindeer soles [J]. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 2017, 33(8): 56—61. (in Chinese with English abstract)
- [28] 张伏, 王亚飞, 马田乐, 等. 山羊蹄底部非规则曲面仿生形貌数学模型构建及验证[J]. *农业工程学报*, 2018, 34(15): 30—36.
Zhang Fu, Wang Yafei, Ma Tianle, et al. Mathematical model construction and verification of bionic topography of irregular surface at the bottom of goat's hoof[J]. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 2018, 34(15): 30—36. (in Chinese with English abstract)
- [29] 田丽梅, 可庆朋, 金娥, 等. 形态/材料耦合仿生功能表面减阻特性及机制[J]. *农业工程学报*, 2015, 31(13): 10—16.
Tian Limei, Ke Qingpeng, Jin E, et al. Surface drag reduction characteristics and mechanism of bionic function of morphological/material coupling[J]. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 2015, 31(13): 10—16. (in Chinese with English abstract)
- [30] 马云海, 裴高院, 王虎彪, 等. 挖掘机獾爪趾仿生斗齿提高其入土性能仿真与试验[J]. *农业工程学报*, 2016, 32(18): 67—72.
Ma Yunhai, Pei Gaoyuan, Wang Hubiao, et al. Simulation and test of bionic bucket teeth of digger badger's claw toe to improve its soil penetration performance[J]. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 2016, 32(18): 67—72. (in Chinese with English abstract)
- [31] 郭俊, 张庆怡, Memon M S, 等. 仿鼯鼠足趾排列的旋耕-秸秆粉碎锯齿刀片设计与试验[J]. *农业工程学报*, 2017, 33(6): 43—50.
Guo Jun, Zhang Qingyi, Memon M S, et al. Rotary tillage-straw crushing saw-tooth blade design and experiment imitating mole toe arrangement[J]. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, 2017, 33(6): 43—50. (in Chinese with English abstract)
- [32] 杨玉婉, 佟金, 马云海, 等. 基于鼯鼠多趾结构特征的仿生切土刀片设计与试验[J]. *农业机械学报*, 2018, 49(12): 122—128.
Yang Yuwan, Tong Jin, Ma Yunhai, et al. Design and experiment of bionic earth-cutting blades based on mole multi-toed structure [J]. *Transactions of the Chinese Society for Agricultural Machinery*, 2018, 49(12): 122—128. (in Chinese with English abstract)
- [33] 王颖, 李建桥, 邹猛, 等. 仿生锥形触土部件水平阻力研究[J]. *农业机械学报*, 2016, 47(S1): 124—129.
Wang Ying, Li Jianqiao, Zou Meng, et al. Study on horizontal resistance of bionic conical soil-touching components[J]. *Transactions of the Chinese Society for Agricultural Machinery*, 2016, 47(S1): 124—129. (in Chinese with English abstract)
- [34] 贾洪雷, 王万鹏, 陈志, 等. 农业机械触土部件优化研究现状与展望[J]. *农业机械学报*, 2017, 48(7): 1—13.
Jia Honglei, Wang Wanpeng, Chen Zhi, et al. Research status and Prospect of optimization of soil-touching components of agricultural machinery[J]. *Transactions of the Chinese Society for Agricultural Machinery*, 2017, 48(7): 1—13. (in Chinese with English abstract)
- [35] 贾洪雷, 罗晓峰, 王文君, 等. 耕作部件耦合仿生表面结构制备方法[J]. *农业机械学报*, 2016, 47(S1): 130—135.
Jia Honglei, Luo Xiaofeng, Wang Wenjun, et al. Fabrication method of bionic surface structure coupled with tillage components[J]. *Transactions of the Chinese Society for Agricultural Machinery*, 2016, 47(S1): 130—135. (in Chinese with English abstract)
- [36] Castanheira P J N, Serralheiro R P. Impact of mole drains on salinity of a vertisoil under irrigation[J]. *Biosystems Engineering*, 2010, 105(1): 25—33.
- [37] James I T, Mann M J, Godwin R J. Design and operational considerations for the use of mole ploughing in the drainage of sports pitches[J]. *Biosystems Engineering*, 2007, 97(1): 99—107.
- [38] 张金波, 佟金, 马云海. 仿生减阻深松铲设计与试验[J]. *农业机械学报*, 2014, 45(4): 141—145.
Zhang Jinbo, Tong Jin, Ma Yunhai. Design and experiment of bionic anti-drag subsoiler[J]. *Transactions of the Chinese Society for Agricultural Machinery*, 2014, 45(4): 141—145. (in Chinese with English abstract)

Development of device for bionic sub-soil liquid fertilizer

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Abstract: The conservation tillage and liquid fertilization can enhance the productivity of farmland. However, soil adhesion occurs on the surfaces of soil-tillage implements during liquid fertilizer applications. Soil adhesion phenomenon can increase energy consumption and decreases fertilizer application quality. The working procedure of liquid fertilizer application by sub-soil liquid fertilizer involves soil compression and shearing, hence, the shape and surface features of the sub-soil liquid fertilizer could significantly affect the performance of soil penetrating, in turn, affect the quality of liquid fertilizer application. Improving the shape design of soil engaging tool is one of the effective methods for reducing operating resistance and increasing working quality. Therefore, a sub-soil liquid fertilizer with novel geometries and surface features should be investigated, and attempts should be made to improve operating efficiency of liquid fertilizer application. Biologically inspired engineering is the application of biological methods found in nature to the study and design of engineering systems. When pressed with an engineering problem in agriculture, engineers could find wisdom and inspirations from the natural world. Through learning from the natural world, it is found that the interactions of living organisms with natural surroundings have led to the evolution of biological systems and environmental adaptabilities. Among the living organisms, earthworms have long been acknowledged to largely contribute to the aggregate stability of soils varying in texture, carbonate, and concentration of organic matter by burrowing, foraging, and casting on the soil surface and within the soil. Besides, earthworms can comfortably move in moist or adhesive soil, it's worth noting that soil particles seldom sticking to bodies. One of the soil fertilization mechanisms for earthworms is that the earthworm swallowed soil and excreted particle casts while burrowing in soil. In this process, the earthworm mucus plays critical roles in adhesion reducing, soil fertilizing and so on. Inspired by this special behavior of earth worm, bionic engineering approach was used and novel method for improving soil fertility were provided in this study. The profile curves of earthworm head and body surface were extracted and fitted using image processing technology. Geometric structure surface of sub-soil liquid fertilizer injection device was designed based on the contour curve equations. The sub-soil liquid injection fertilizer devices (3 injection holes and 6 injection holes) which matched with the bionic subsoiler, were designed. Ultra-high molecular weight polyethylene (UHMWPE) was chosen as the material for manufacture this device. The significant influence of factors for investigation was the liquid injection, the number of holes, the materials and the surface structure for drag resistance, and the surface structure, the number of holes, the materials and the liquid injection for soil adhesion. The prototype performances were tested by using soil bin test system. The performance parameters of holes, liquid injection, material and geometrical structure surface were taken into account to present the effects on drag-reducing and anti-soil adhesion in tests. The results showed that the significant influences of the performance parameters for drag resistance were as liquid injection > hole number > material > surface structure. The significant influences of the performance parameters for soil adhesion were surface structure > hole number > material > liquid injection. The optimal level of each parameter was the liquid injection, six holes, UHMWPE material and geometrical structural surface. The optimized prototype was selected from eight types of sub-soil liquid fertilizer injection devices, which was UHMWPE in material, with geometry structure surface and six liquid injection holes. In the same experiment conditions, the mean value of the drag resistance of the selected bionic prototype was 283.48 N, the mean weight of soil adhesion was 10.93 g, which was lower than that of other prototypes. This study provided technical references for the mechanization of sub-soil fertilizing engineering.

Keywords: bionics; design; geometric structured surface; drag-reducing; sub-soil liquid fertilizer injection; earthworm