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水稻机械直播的土壤表层泥浆离散元参数标定

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摘要:【目的】针对水稻机械直播稻田播前土壤与触土部件的相互作用机理不明确等问题,可利用离散元分析法研究影响水稻精量穴直播质量的因素。由于播前土壤的结构复杂,其表层泥浆与耕层存在一定差异,因此,需分层构建复合土壤模型。为获取精确的水稻机械直播的表层泥浆离散元参数,开展试验研究和仿真分析,并标定表层泥浆的离散元仿真参数。【方法】按照水稻精量穴直播的整地要求处理,并在播种前去田间获取表层泥浆,采用漏斗法进行泥浆堆积角试验,利用数显倾角仪多次测量泥浆堆积角并取平均值。选择EDEM离散元软件中Hertz-Mindlin with JKR接触模型,开展泥浆堆积角仿真试验。以堆积角为响应值,通过Plackett-Burman试验筛选出对堆积角影响显著的3个参数,进一步开展最陡爬坡试验缩小显著性参数的取值范围。采用Box-Behnken试验建立表层泥浆堆积角与筛选的显著性参数的回归模型,并以物理试验测得的泥浆堆积角为目标值,对显著性参数寻优得到最佳参数组合。将最优参数代入仿真软件验证表层泥浆颗粒离散元参数的准确性。【结果】泥浆堆积角物理试验获取表层泥浆堆积角为40.20°。Plackett-Burman试验结果表明,泥浆剪切模量、泥浆-泥浆表面能和泥浆-钢表面能对表层泥浆堆积角有显著性影响,其余试验因素对堆积角的影响均不显著。最陡爬坡试验将显著性参数的最优区间缩小为:泥浆剪切模量1.6~4.6 MPa、泥浆-泥浆表面能0.25~0.35 J/m²、泥浆-钢表面能0.02~0.04 J/m²。通过堆积角回归模型,获取最优解为:泥浆剪切模量1.839 MPa、泥浆-泥浆表面能0.25 J/m²、泥浆-钢表面能0.029 J/m²。将最优参数仿真软件验证的结果为39.10°,与泥浆堆积角物理试验结果的相对误差为2.74%。【结论】基于Hertz-Mindlin with JKR接触模型标定的水稻机械直播的表层泥浆颗粒离散元参数准确可靠,可为构建水稻机械直播稻田土壤的离散元模型提供理论依据。

关键词:水稻;机械直播;土壤;表层泥浆;离散元;参数标定;堆积角
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Calibration of discrete element parameters for soil surface mud in mechanical direct seeding of rice

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Abstract:[**Objective**] In order to solve the problem that the interaction effect between the mechanical direct seeder and the preceding seeding soil was not very clear, the discrete element method was applied to study the factors affecting the quality of precision rice hill-drop drilling.Due to the complex structure of the soil before sowing and a certain difference between the surface mud and the plough layer, it is necessary to construct a composite soil model in layers. For obtaining accurate discrete element parameters of surface mud for mechanical direct seeding, the experiments and simulations analysis were conducted, the discrete element model of the soil surface mud was built by calibrating the key parameters.[**Method**] The tillage requirement of field was the same as the precision rice hill-drop drilling, the surface mud was collected before sowing, the mud accumulation angle test was conducted by funnel method, The mud accumulation angle was measured many times by digital display inclinometer and the average value was calculated. Hertz-Mindlin with JKR contact model in the EDEM discrete element software was selected to simulate the soil surface mud. Taking the accumulation angle as the response value, the Plackett-Burman experiments were applied to screen out the three parameters which had a significant impact on the accumulation angle, and the steepest ascent experiments were conducted to narrow down the range of three significant parameters. The regression equation of the accumulation angle was established with the selected significant parameters by using Box-Behnken experiments, Taking the mud accumulation angle measured by physical test as the target value, the optimal parameter combination was obtained by optimizing the significant parameters.Then the optimal parameters were substituted into the EDEM to verify the accuracy of discrete element parameters of surface mud particles. [**Result**] The physical test of mud accumulation angle showed that the surface mud accumulation angle was 40.20°, and Plackett-Burman experimental results showed that the mud shear modulus, the mud-mud surface energy and the mud-steel surface energy had significant effects on the surface mud accumulation angle, the other test factors had no significant effect on it.The steepest ascent experimental results showed that the optimal range of significant parameters were as follows: the mud shear modulus was 1.6-4.6 MPa, the mud-mud surface energy was 0.25-0.35 J/m^2, the mud-mud surface energy was 0.02-0.04 J/m^2.Through the regression model of accumulation angle, the optimal parameters were obtained: the mud shear modulus 1.839 MPa, the mud-mud surface energy 0.25 J/m^2, and the mud-steel surface energy 0.029 J/m^2. The results verified by the optimal parameter simulation software were 39.10°, and the relative error with the physical test results of the mud accumulation angle was 2.74%.[**Conclusion**] The above tests showed that the discrete element parameters of surface mud particles calibrated by the Hertz-Mindlin with JKR contact model for mechanical direct seeding of rice were accurate and reliable.This study showed that the surface mud of preceding seeding soil was accuracy, and the results would be used for building the compound discrete element model of the mechanical direct seeding of rice.

Keywords: rice; mechanical direct seeding; soil; surface mud; discrete element; parameter calibration; accumulation angle

【研究意义】离散元法被广泛应用于分析土壤颗粒间及其与触土部件的相互作用,且精准离散元模型可用于分析其互作机理和获取关键参数,而标定仿真参数是构建精准模型的关键。目前干燥稻田和旱地的土壤离散元研究较成熟,但湿润稻田的土壤离散元研究较少,尤其是水稻机械直播的湿润土壤离散元研究。相关研究[1]表明,环鄱阳湖区域的播前土壤性质相似,可建立一种通用的土壤模型。由于播前土壤的表层泥浆含水率高、流动性强,因此,构建精准机械直播的土壤离散元模型,需标定土壤表层泥浆的离散元参数。【前人研究进展】Ucgul等[2]利用离散元法标定了沙壤土参数;Aikins等[3-5]研究了沙壤土与弯腿式开沟器的相互作用,分析了倾角、前进速度与开沟深度对土壤扰动的影响;王宪良等[6]提出了一种以堆积角为响应值标定沙壤土离散元参数的方法,且误差小于5.10%;方会敏等[7-9]以粘土为原型(47%淤泥、42%粘土和11%沙),建立了土壤+秸秆混合模型,研究了土壤与旋耕刀间的互作规律;孙景彬等[10]

标定了黄土高原坡地粘壤土与65 Mn钢的仿真参数；石林榕等[11]建立了西北旱区农田土壤含水率1%~20%的离散元模型，抗剪强度相对误差为1.18%~9.31%；张锐等[12]提出了一种标定砂土颗粒参数的方法，并研究了颗粒质量、标定方法（抽板法和漏斗法），以及标准球对堆积角的影响；丁启朔等[13]建立了土壤深度0~40 cm耕层和底层的复合深松土壤模型，明确了深松铲与土壤相互作用的机理；王曦成等[14]构建了湿黏土壤的离散元模型，明确了入土深度10 cm，刀具转速3 r/s和前进速度1 m/s条件下，土壤阻力为53.20 N，可处理85%秸秆杂草。【本研究切入点】目前众多学者借助Hertz-Mindlin with JKR接触模型标定了粘壤土参数，但与机械直播的播前土壤机械物理参数存在一定差异，且尚未有机械直播的土壤表层泥浆离散元研究报道。【拟解决的关键问题】以播前土壤为研究对象，基于Hertz-Mindlin with JKR接触模型，开展土壤表层泥浆堆积角物理试验和仿真试验，标定其离散元仿真参数，为构建水稻机械直播稻田土壤的离散元模型等提供参考。

1 材料与方法

1.1 试验材料

由于用土壤与水配制的对应含水率泥浆与实际田间表层泥浆的性状存在差异，故本试验材料选用稻田土壤表层原状泥浆，取自江西省南昌市江西农业大学农业科技园。为了表层泥浆更接近水稻机械直播作业时的田间状态，按照水稻精量穴直播的整地要求[15]，在稻田经过水旋耕和人工平整后，沉淀1~2 d排水处理，随后对0~1 cm表层泥浆原状土进行采样。表层泥浆容重为2.07 g/cm^3，进行含水率测量时，借助DH190卤素灯水分仪用烘干法计算含水率如表1所示，结果表明表层泥浆的平均绝对含水率为86.5%。

表1 表层泥浆含水率

Tab.1 Mud moisture content

样本 Sample	湿土质量/g Wet soil weight	干土质量/g Dry soil weight	相对含水率/% Relative moisture content	绝对含水率/% Absolute moisture content
1	1.53	0.84	45.10	82.14
2	1.45	0.81	44.14	79.01
3	2.23	1.14	48.88	95.61
4	3.30	1.78	46.06	85.39
5	1.77	0.93	47.46	90.32
均值 Average	2.06	1.10	46.33	86.50

1.2 试验方法

物料颗粒在自然状态下形成的堆积角是一定的，是颗粒物料流动性和接触参数等的宏观表现形式[16]。因此将泥浆堆积角作为一个重要参数，采用堆积角物理试验与仿真试验相结合的方式来标定泥浆颗粒的接触参数。堆积角测量装置如图1所示，由钢制漏斗、铁架、钢板组成。漏斗入口直径为

1：钢制漏斗；2：铁架；3：钢板。

1：Steel funnel；2：Iron frame；3：Steel plate.

图1 实际堆积角测定试验装置

Fig.1 Actual accumulation angle determination test device

145 mm,出口直径为15 mm,钢制漏斗固定在漏斗出口与钢板相距75 mm的位置。

试验时,将水稻机械直播的田块处理好,称取相同质量的表层原状泥浆,将其缓缓倒入漏斗内,直至漏斗内的泥浆漏完并自然堆积在钢板上,形成泥浆堆,用数显倾角仪从泥浆堆的不同方向测量,如图2所示。如此重复5次,结果表明,泥浆平均堆积角为40.20°。

图2　泥浆实际堆积角测量

Fig.2　Measurement of actual accumulation angle of mud

2　表层泥浆参数标定

2.1　构建表层泥浆离散元模型

颗粒接触模型是离散元仿真的核心,而播前土壤的表层泥浆含水率高,土壤颗粒受水分子影响以液桥力粘结在一起,液桥力由毛细力和粘性力组成[17]。EDEM中的Hertz-Mindlin with JKR接触模型(简称JKR模型)中表面能可模拟颗粒的粘结力,故选用JKR模型作为表层泥浆的颗粒接触模型。

EDEM本征参数有密度、颗粒体几何尺寸、剪切模量和泊松比等;基本接触参数包括颗粒与颗粒、颗粒与材料间的恢复系数、静摩擦系数、滚动摩擦系数。目前水稻机械直播的播前土壤表层泥浆研究尚未有相关报道,无法获取精准的仿真参数,因此,通过参考GEMM数据库和其他土壤离散元研究[18-21],获取表层泥浆仿真参数范围,如表2所示。

建立表层泥浆堆积角离散元模型,设置漏斗出口与钢板距离为75 mm,选择泥浆颗粒半径1 mm单球

表2　表层泥浆仿真参数范围

Tab.2　Range of values for simulation model parameters

参数 Parameter	数值 Value	参数 Parameter	数值 Value
泥浆密度/(g·cm^{-3}) Density of mud	2.07	泥浆-泥浆静摩擦系数 Static friction coefficient between mud	0.05~0.10^{a}
泥浆泊松比 Poisson ratio of mud	0.25~0.5^{a}	泥浆-泥浆滚动摩擦系数 Rolling friction coefficient between mud	0.05~0.20^{a}
泥浆剪切模量/MPa Shear modulus of mud	0.1~100^{a}	泥浆-钢恢复系数 Recovery coefficient between mud and steel	0.05~0.20^{a}
钢密度/(g·cm^{-3}) Density of steel	7.8	泥浆-钢静摩擦系数 Static friction coefficient between mud and mud	0.05~0.20^{a}
钢泊松比 Poisson ratio of steel	0.3	泥浆-钢滚动摩擦系数 Rolling friction coefficient between mud and steel	0.05~0.20^{a}
钢剪切模量/MPa Shear modulus of steel	79 000	泥浆-泥浆表面能/(J·m^{-2}) JKR surface energy between mud	0.2~0.40^{a}
泥浆-泥浆恢复系数 Recovery coefficient between mud	0.05~0.2^{a}	泥浆-钢表面能/(J·m^{-2}) JKR surface energy between mud and steel	0.01~0.05^{a}

上标a表示试验变量。

Superscript a indicates the test variable.

型，颗粒生成总质量与取样质量保持一致，设置时间积分为Euler，仿真时间步长为20% Rayleigh时间步长，网格为2.5 mm，开始运行仿真计算，获取泥浆颗粒堆积角。通过对泥浆颗粒仿真堆积角的原始图像灰度化处理，提取图像轮廓像素点坐标，并拟合边缘曲线，计算仿真堆积角，如图3所示。

a.原始图像
a.Original image

b.灰度图像
b.Grayscale image

c.轮廓线提取
c.Extracted contour line diagram

图3 表层泥浆仿真堆积角
Fig.3 Simulation accumulation angle of surface mud

2.2 仿真试验设计

2.2.1 Plackett-Burman 试验

为明确表层泥浆参数对堆积角影响的显著性，以堆积角为响应值，选择10个待确定参数和1个虚拟参数为试验因素，应用Plackett-Burman Design试验筛选显著性参数，并确定参数上限值和下限值，如表3和表4所示。

表3 Plackett-Burman试验因素与水平
Tab.3 Plackett-Burman test factors and levels

参数 Parameter	低水平 Low level	高水平 High level	参数 Parameter	低水平 Low level	高水平 High level
泥浆泊松比 *A*	0.25	0.50	泥浆-钢恢复系数 *F*	0.05	0.20
泥浆剪切模量/MPa *B*	0.10	100.00	泥浆-钢静摩擦系数 *G*	0.05	0.20
泥浆-泥浆恢复系数 *C*	0.05	0.20	泥浆-钢滚动摩擦系数 *H*	0.05	0.20
泥浆-泥浆静摩擦系数 *D*	0.05	0.10	泥浆-泥浆表面能/($J·m^{-2}$) *J*	0.20	0.40
泥浆-泥浆滚动摩擦系数 *E*	0.05	0.20	泥浆-钢表面能/($J·m^{-2}$) *K*	0.01	0.05

表4 Plackett-Burman试验结果
Tab.4 Plackett-Burman test scheme and results

序号 Serial number	试验因素 Test factors											堆积角θ/(°) Accumulation angle
	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*J*	*K*	*L*	
1	1	1	−1	1	1	1	−1	−1	−1	1	−1	32.9
2	−1	1	1	−1	1	1	1	−1	−1	−1	1	55.9
3	1	−1	1	1	−1	1	1	1	−1	−1	−1	18.4
4	−1	1	−1	1	1	−1	1	1	1	−1	−1	66.6
5	−1	−1	1	−1	1	1	−1	1	1	1	−1	14.85
6	−1	−1	−1	1	−1	1	1	−1	1	1	1	6.4
7	1	−1	−1	−1	1	−1	1	1	−1	1	1	5.3
8	1	1	−1	−1	−1	1	−1	1	1	−1	1	65.4
9	1	1	1	−1	−1	−1	1	−1	1	1	−1	44.7
10	−1	1	1	1	−1	−1	−1	1	−1	1	1	36.6
11	1	−1	1	1	1	−1	−1	−1	1	−1	1	11.6
12	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	7.8

试验分析结果如表5所示。由结果可知，泥浆剪切模量、泥浆-泥浆表面能、泥浆-钢表面能的*P*值均小于0.05，表明此3个因素均对表层泥浆堆积角影响显著。

表 5　Plackett-Burman 试验结果分析

Tab.5　Significance analysis of Plackett-Burman test parameters

因素 Factors	效应 Effects	平方和 Sum of squares	影响率/% Contribution	*P* 值 *P* value	显著性排序 Significance ranking
A	-1.64	8.09	0.137 3	0.248 3	8
B	39.63	4 710.42	79.964 3	0.010 8	1
C	-0.39	0.46	0.007 8	0.665 3	10
D	-3.58	38.34	0.650 9	0.118 8	6
E	1.31	5.14	0.087 2	0.303 2	9
F	3.54	37.63	0.638 8	0.119 9	7
G	4.69	66.04	1.121 0	0.091 0	5
H	7.97	190.80	3.239 1	0.053 8	4
J	8.78	231.00	3.921 5	0.048 9	3
K	-14.16	601.38	10.209 0	0.030 3	2

2.2.2　最陡爬坡试验

为获取影响表层泥浆堆积角的显著性参数中心值,选取泥浆剪切模量、泥浆-泥浆表面能、泥浆-钢表面能为试验因素开展最陡爬坡试验,如表6所示。试验结果表明:随着泥浆剪切模量(B)、泥浆-泥浆表面能(J)逐渐增大,表层泥浆堆积角的相对误差先减小后增大。当泥浆剪切模量为3.1 MPa、泥浆-泥浆表面能为0.3 J/m^{2}时,堆积角的相对误差最小,为8.21%。

表 6　最陡爬坡试验结果

Tab.6　Test scheme and results of the steepest climb

序号 Serial number	试验因素 Test factors			堆积角 *θ*/(°) Accumulation angle	相对误差/% Relative error
	B	*J*	*K*		
1	0.1	0.20	0.05	4.35	89.18%
2	1.6	0.25	0.04	35.9	10.70%
3	3.1	0.30	0.03	43.5	8.21%
4	4.6	0.35	0.02	50.8	26.37%
5	6.1	0.40	0.01	60.5	38.56%

2.2.3　Box-Behnken 试验

为建立泥浆剪切模量、泥浆-泥浆表面能、泥浆-钢表面能与表层泥浆堆积角之间的回归模型,开展Box-Behnken试验研究,选取泥浆剪切模量为3.1 MPa、泥浆-泥浆表面能为0.3 J/m^2、泥浆-钢表面能为0.03 J/m^{2}作为中间水平,选择泥浆剪切模量范围1.6~4.6 MPa、泥浆-泥浆表面能范围0.25~0.35 J/m^2、泥浆-钢表面能范围0.02~0.04 J/m^{2}作为试验高水平和低水平,结果如表7所示。

方差分析结果如表8所示。结果表明:泥浆剪切模量对堆积角影响极显著,泥浆-泥浆表面能、泥浆剪切模量和泥浆-泥浆表面能的乘积、泥浆-钢表面能的平方均对堆积角影响非常显著,泥浆-钢表面能、剪切模量的平方、泥浆-泥浆表面能的平方均对泥浆堆积角影响显著,此堆积角拟合模型(P=0.000 11)显著,失拟项(P=0.753 3)不显著,表明模型拟合程度较好;且模型决定系数R^2=0.991 8,变异系数为1.54%。该方程可用于预测表层泥浆的堆积角。

建立表层泥浆堆积角回归方程,如公式(1)所示:

$$\theta = 45.3 + 4.625B + 1.725J + 1.15K + 1.4BJ - 1.9B^2 + 0.8J^2 + 2.45K^2 \quad (1)$$

式中,θ为泥浆堆积角,(°);B为泥浆剪切模量,MPa;J为泥浆-泥浆表面能,J/m^2;K为泥浆-钢表面能,J/m^2。

2.3　验证试验

以实测表层泥浆堆积角40.20°为目标值,以泥浆剪切模量范围1.6~4.6 MPa、泥浆-泥浆表面能范围

表 7 Box-Behnken试验仿真结果

Tab.7 Box-Behken test design and result

序号 Serial number	试验因素 Test factors			堆积角 θ/(°) Accumulation angle
	B/MPa	*J*	*K*	
1	-1(1.6)	-1(0.25)	0(0.03)	38.9
2	1(4.6)	-1	0	45.5
3	-1	1	0	40.1
4	1	1(0.35)	0	52.3
5	-1	0(0.3)	-1	40.4
6	1	0	-1(0.02)	48.7
7	-1	0	1(0.04)	42.2
8	1	0	1	52.1
9	0(3.1)	-1	-1	45.7
10	0	1	-1	49.4
11	0	-1	1	48.5
12	0	1	1	50.6
13	0	0	0	46.1
14	0	0	0	44.5
15	0	0	0	45.3

表 8 Box-Behnken试验回归模型方差分析

Tab.8 A nova of quadratic polynomial model of Box-Behnken test

方差来源 Source of variance	平方和 Sum of square	自由度 Degree of freedom	*F*值 *F* value	*P*值 *P* value
模型 Model	255.154 0	9	67.18	0.000 11**
B	171.125 0	1	405.51	<0.000 1***
J	23.805 0	1	56.41	0.000 7**
K	10.580 0	1	25.07	0.004 1*
BJ	7.840 0	1	18.58	0.000 76**
BK	0.640 0	1	1.52	0.272 9
JK	0.640 0	1	1.52	0.272 9
B^2	13.329 2	1	31.59	0.002 5*
J^2	2.363 0	1	5.60	0.006 42*
K^2	22.163 08	1	52.52	0.000 8**
残差 Residual	2.11	5		
失拟项 Lack of fit	0.83	3	0.43	0.753 3
R^2=0.991 8;R_a^2=0.977 0;CV=1.54%;Adeq precisior=24.085				

***表示极显著水平(P<0.001),**表示非常显著水平(0.001<P<0.01),*表示显著水平(0.01<P<0.05)

***indicates a highly significant level(P<0.001),** indicates a very significant level(0.001<P<0.01),* indicates a significant level(0.01<P<0.05)

0.25~0.35 J/m²、泥浆-钢表面能范围0.02~0.04 J/m²为约束条件,求解公式(1)堆积角回归方程进行求解寻,获取最优解为:泥浆剪切模量1.839 MPa、泥浆-泥浆表面能0.25 J/m²、泥浆-钢表面能0.029 J/m²。基于泥浆最优解组合开展离散元仿真试验,得到堆积角为39.10°,与实际堆积角的相对误差为2.74%,如图4所示。

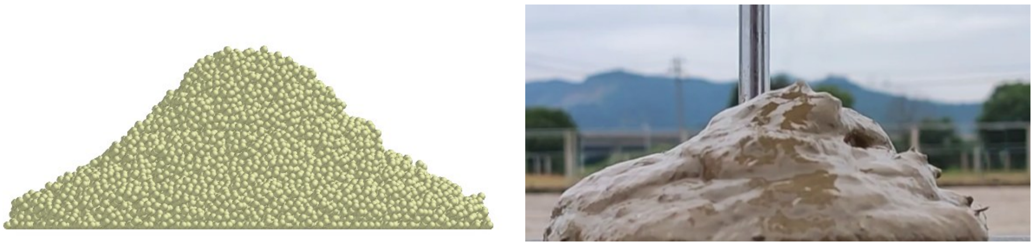

图4　稻田泥浆堆积角仿真与实测结果

Fig.4　Simulation and measured map of paddy mud accumulation angle

3　结　论

基于Hertz-Mindlin with JKR接触模型,开展了水稻机械直播的土壤表层泥浆堆积角离散元仿真。通过Plackett-Burman试验和最陡爬坡试验,明确了影响泥浆堆积角的显著性因素及其最优区间:泥浆剪切模量为1.6~4.6 MPa、泥浆间表面能为0.25~0.35 J/m^2、泥浆与钢表面能为0.03~0.04 J/m^2;并通过Box-Behnken试验,建立了堆积角的回归方程。

以表层泥浆实际堆积角为优化目标值,利用回归方程求解,获得最优解为:泥浆剪切模量1.839 MPa、泥浆-泥浆表面能0.25 J/m^2、泥浆-钢表面能0.029 J/m^2。验证试验结果表明:堆积角仿真值误差为2.74%,可满足水稻机械直播的土壤离散元仿真要求。本研究可为构建水稻机械直播稻田土壤的离散元模型提供理论依据。

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