Optimization of working parameters for puddling and flatting machine in paddy field

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Abstract: In order to improve the soil preparation quality, a wide puddling and flatting machine for paddy field was designed with the functionality of tillage, soil crushing, puddling, burying stubble and flatting in one-time operation, which can be equipped on tractors with high power. This study focused on the design and analysis of key components of the machine including puddling equipment, flat shovel and balance structure. Optimal results with field trials and response surface analysis showed that the machine can operate optimally when the working speed, puddling depth and angle of flat shovel were 1.05 km/h, 16 cm and 31.30°, respectively. The surface flatness standard deviation was 3.7 cm, and slurry degree was 1.03 g/cm^3. Field validation test results were consistent with the optimal parameters, which was able to meet agronomic requirements of mechanical planting in China.

Keywords: paddy field, puddling and flatting machine, rice production, design, field test, optimization
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1 Introduction

Rice is one of the three major grain crops in China. The total grain output of China reached 589.5 billion kg in 2013, of which rice output reached 204.3 billion kg, accounting for 34.65% of grain production of China[1,2]. Hence rice output plays an important role in the grain production. The increased rice output of China mainly benefited from the application of much relatively modern agricultural machinery, among which planting machinery grew fastest. However, the machines for soil preparation of paddy field developed slowly.

In the past years, soil preparation of paddy field was conducted by traditional plow tillage or steeping field after rotary tillage, and then by rolling several times with water harrowing wheel to complete the soil crushing and puddling work[3-6]. The process mainly relied on passive rolling, which caused many problems such as frequent work and low efficiency.

In recent years, some agricultural companies in China, such as Haofeng Agricultural Machine Company and Jifeng Agricultural Chain Machine Company, have improved puddling machine for paddy field by the rotary tiller principle[7,8]. Although it can bury stubble, crush the soil and puddle after field steeping once, the problems existed commonly after working such that the paddy field was not flat and slurry layer depth was uneven after slurry sediment.

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Application of paddy field flat in China mainly used traditional profile modeling flatting techniques such as raking and rolling, which were difficult to achieve better flat requirements. Some research institutes, such as China Agricultural University, Huazhong Agricultural University, US Trimble and Japan Topcon, have carried out researches and developed laser flatting machines for paddy field, which used the structure of a double-acting hydraulic cylinder for contraction under the control of signal received by the sensor to change the level of flat shovel[9-11]. The advantage of the structure is to ensure the quality of flat of paddy field, while accompanied disadvantages including higher costs, unstable working process, influence of external environment, small working width of usually no more than 210 cm, and difficultly in combining work with other preparation machines of paddy field.

Based on the above considerations, Research Institute of Agricultural Mechanization of Harbin of China developed a puddling and flatting machine for paddy field (1JPS-600). It can complete individual works with a strong practicability to meet the different needs of farming.

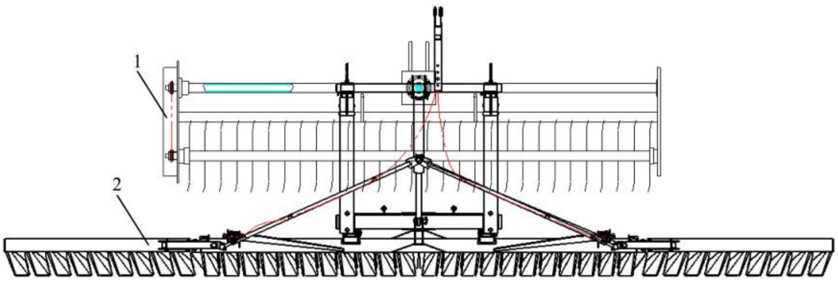
2 Structural parameters and working principle

2.1 Structural parameters

The puddling and flatting machine of 1JPS-600 for paddy field mainly consisted of puddling equipment and flatting equipment. The structure parameters, structure diagram and working condition of the machine are shown in Table 1 and Figure 1, respectively.

Table 1 Structural parameters

Parameters	Value
Matched power/kW	65
Working width/cm	600
Puddling depth/cm	8-16
Gross weight of machine /kg	575
Working efficiency/hm^2 h^{-1}	0.8-1.4
Pressure stubble depth/cm	≥5



1. Puddling equipment 2. Flatting equipment

a. Structure diagram

b. Working condition of the puddling and flatting machine

Figure 1 Structure diagram and working condition of 1JPS-600 puddling and flatting machine for paddy field

2.2 Working principle

Flatting equipment of the investigated machine was developed by connecting a plate on the beam of the puddling equipment[12-15]. The puddling equipment was connected with the tractor by a three-point suspension system. During application of the equipment, the power of the tractor was transmitted by universal joint and transmission[16], driving puddle blade rotating rapidly. The puddle blades were arranged in double-helix and fixed on the blade roller. And the puddle blades peeled the steeping field (2 d) and completed crushing, puddling and burying. Then the retaining plate blocked the slurry and stubble, stirred them together[17-19], and flatted the peeling slurry under the role of flatting equipment.

3 Design of key components

3.1 Puddling equipment

3.1.1 Structure of puddling equipment

Puddling equipment mainly consisted of power transmission systems, frames, soil crashing and puddling working system, etc. The power transmission system consisted of universal joints, gearbox and other components, and it was used to transmit the tractor power to the crashing shaft in accordance with a certain speed (the speed is adjustable according to agronomic requirements). The crashing and puddling working system mainly consisted of puddle blade shaft, tool magazine and puddle blade. The tool magazine was arranged in a spiral and welded to the puddle blade shaft. The puddle blade using special curved blade was installed in the tool magazine by bolted joints.

3.1.2 Determination of maximum puddling depth

During the operation of the puddling equipment, absolution motion of puddle blade was the synthesis of puddle blade shaft rotation and the horizontal movement of the puddling equipment. The moving of orbit should be cycloid (Figure 2). Taking the center '*o*' of the rotary puddle blade shaft as the origin of coordinates, the puddling equipment forward direction as *x* axis and depth direction as *y* axis.

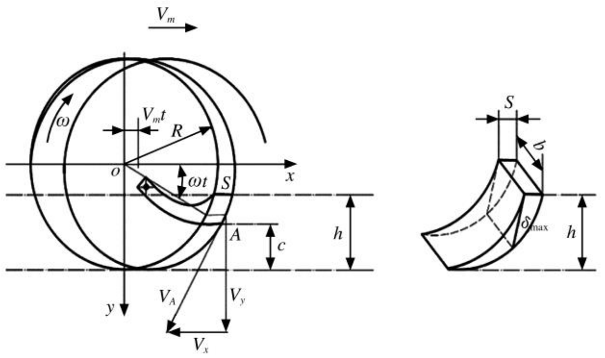


Figure 2 Moving orbit of puddle blade

From the analysis of the moving orbit of the puddle blade, the motion equations of the puddle blade endpoint are:

$$\begin{cases} x = V_m t + R\cos\omega t \\ y = R\sin\omega t \end{cases} \tag{1}$$

where, R is radius of rotation of puddle blade shaft, mm; V_m is forward velocity of the unit, m/s; ω is rotation angular velocity of the puddle blade shaft, rad/s; t is time, s; The velocities in the directions of x and y axes for the puddle blade endpoint are:

$$\begin{cases} V_x = dx/dt = V_m - R\omega\sin\omega t \\ V_y = dy/dt = R\omega\cos\omega t \end{cases} \tag{2}$$

Set the puddle equipment depth h, as shown in Figure 2. At the beginning of puddle blade cutting into the soil, the value of y is:

$$y = R - h = R\sin\omega t$$

When the puddle blade begins cutting with V_x<0, the moving orbit of each point of cutting part on the edge is trochoid. That is the absolute velocity of the blade pointed down and the blade back works normally rather than bulldozed.

$$V_x = V_m - R\omega\sin\omega t = V_m - (R-h)\omega$$

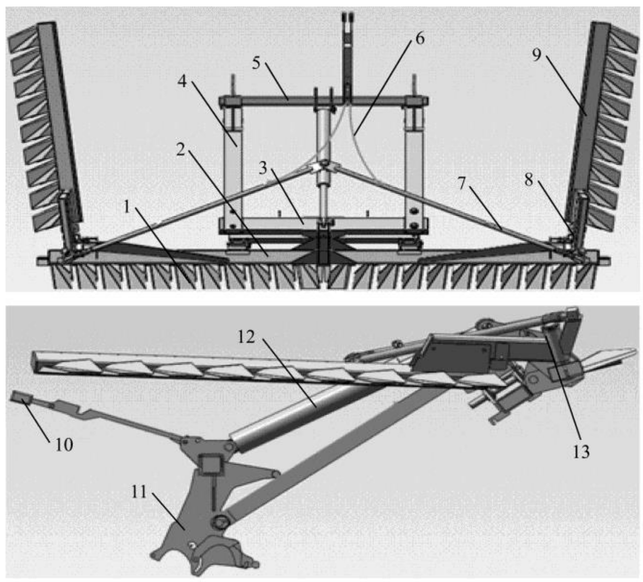
Therefore, the condition of the deeply cutting soil of the puddle blade is:

$$h < R - V_m/\omega \tag{3}$$

Three factors including R, V_m and ω can be determined before working, thus the maximum puddle depth can be determined by Equation (3).

3.2 Flatting equipment

Flatting equipment (Figure 3) consisted of frames, folding system, flat shovel and balance structure. The frames were made up of main frame, side frame and other components. Main frame was connected to the puddling equipment and side frame was mainly used for the installation of the flat shovel[20,21]. The folding system mainly consisted of a hydraulic system, which achieved longitudinal and vertical folding of flat shovel and side frame. Flat shovel was made up of flatting plate and moldboard. The balance structure was made of flexible beam to achieve in restraining the flatting equipment with the change of the terrain.



1. Flat shovel 2. Main frame 3. Flexible beam 4. Connecting beam 5. Front beam 6. Stretch 7. Bar 8. Stretchbukckle 9. Side frame 10. Stretch spanner 11. Connecting plate 12. Hydraulic cylinder 13. Hinge pin

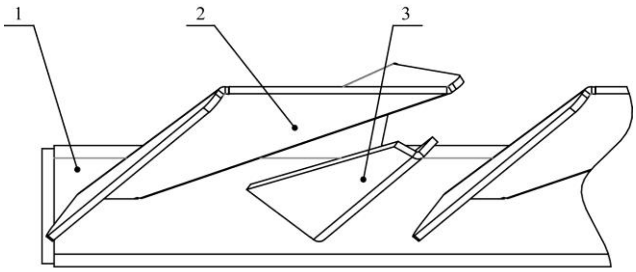
Figure 3 Structure of the flatting equipment

3.2.1 Flat shovel

Flat shovel was welded to the frame and designed to lift with the change of telescopic hydraulic cylinder[22-24]. Both side frames of flat shovel rotated around the hinge pin in the role of hydraulic cylinders, which barred by gravity during the lifting. When reaching the upper limit, they would be locked by stretch buckle under the action of the spring to achieve in folding process.

1) Structure of flat shovel

Flat shovel contacted soil directly and affected the quality of flatting work. Its structure is shown in Figure 4.



1. Frame 2. Flat plate 3. Moldboard

Figure 4 Structure of flat shovel

2) Working width of flat shovel

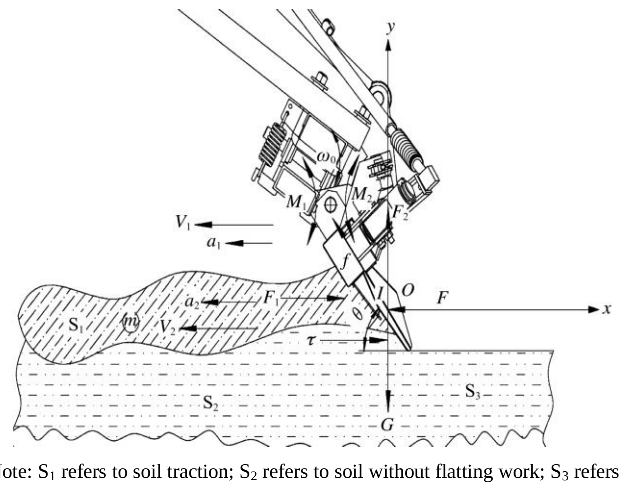
Working width of the flat shovel can be determined by the following equation:

$$B = \frac{P_h}{nP}\eta_P \tag{4}$$

where, B is working width of the flat shovel, cm; P_h is rated traction force, N; P is mean resistance, N; n is number of the flat shovel; η_p is utilization factor, η_p = 0.15.

3) Mechanical model of flat shovel

Force analysis of flat shovel is shown in Figure 5.



Note: S_1 refers to soil traction; S_2 refers to soil without flatting work; S_3 refers to soil after flatting work.

Figure 5 Force analysis of flat shovel

When flat shovel is working, the balance equations of flat shovel in plane *xoy* are:

$$\sum F_x = F - F_1 - f\cdot cos\theta - {G}/{g}\cdot a_1 = 0 \tag{5}$$

$$\sum F_y = F_2 - G - f\cdot sin\theta = 0 \tag{6}$$

$$\sum M_{xoy} = M_1 - M_2 - I\cdot\frac{d\omega_0}{dt_0} = 0 \tag{7}$$

where, $F_1 = \tau + ma_2$, $f = F_1 sin\theta\cdot\mu_1$, $\tau = \mu_2 F_2 + Qc$ (Moore – Coulomb's Law). m is mass of soil in S1 zone, kg; V_2 is traction velocity of S1 zone soil, m/s; a_2 is accelerated traction velocity of S1 zone soil, m/s^2; V_1 is horizontal velocity of flat shovel, m/s; a_1 is horizontal accelerated velocity of flat shovel, m/s^2; F is horizontal traction force, N; G is gravity of flat shovel, N; F_1 is horizontal bearing reaction of flat shovel, N; F_2 is vertical bearing reaction of flat shovel, N; f is friction of flat shovel, N; τ is resistance to shear force of S2 zone soil, N; θ is angle between flat shovel and horizontal plane, (°); ω_0 is angular velocity of flat shovel, rad/s; M_1 is rotating torque of flat shovel, N·m; M_2 is rotating resistance moment of flat shovel, N·m; I is rotating inertia of flat shovel, kg·m^2; g is acceleration of gravity, m/s^2; u_1 is friction coefficient between flat shovel and soil; u_2 is friction coefficient between soil; Q is contact area between flat shovel and soil, m^2; c is cohesion of soil, N.

3.2.2 Balance structure

Balance structure is an important working part of the investigated machine for keeping the soil contact working and maintaining a certain working depth with the change of the terrain to adapt to the uneven part of paddy field[25]. When working, balance structure in the horizontal direction is automatically adjusted by connecting the upper and lower springs of the flexible beam. Balance structure in the forward direction is conducted by four-bar mechanism (Figure 6).

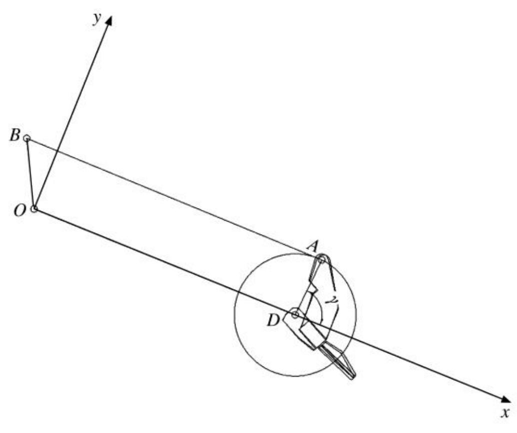


Figure 6 Diagram of four-bar balance mechanism

From Figure 6, B and A are the upper and lower connection points of the hydraulic cylinder, O is the upper connection point of the connecting beam and *D* is the connection point of main frame and flexible beam. *O* is considered as the origin of coordinates and *OD* as the *x* axis forward direction to make a Cartesian coordinate. γ is the angle between *AD* and the *x* axis forward direction. During the lifting of the flatting equipment, *O* and *B* were the fixed points, moving orbit of *D* is a circle with the center of *O* and the radius of *OD*, and moving orbit of *A* is a circle with the center of *D* and the radius of *DA*. Because *AD* is the shortest bar, the four-bar balance mechanism is a double-rocker and bar-length-variable four-bar mechanism. Taking the hydraulic cylinder (*AB*) as the driving link, degrees of freedom of the four-bar mechanism[26] is:

$$F=1$$

When *OD* reached the lower limit position, the hydraulic cylinder continued to elongate, then *D* turned into the fixed point, and only *A* continued to rotate circularly. Parameter equation of the rotation of *A* around *D* is:

$$\begin{cases} x_A = x_D + l_{DA}\cos\gamma \\ y_A = l_{DA}\sin\gamma \end{cases} \tag{8}$$

Length of hydraulic cylinder *AB* is:

$$l_{AB}=\sqrt{(x_A-x_B)^2+(y_A-y_B)^2} \tag{9}$$

By substituting Equation (8) into Equation (9), so

$$l_{AB}=\sqrt{(x_D-x_B)^2+l_{DA}{}^2+y_B{}^2-2l_{DA}\sqrt{(x_B-x_D)^2+y_B{}^2}\sin(\gamma+\arctan\frac{x_B-x_D}{y_B})} \tag{10}$$

Substituting data, derived equation of the change of γ caused by the elongation of the hydraulic cylinder is

$$\gamma=\arcsin\frac{1554029-l_{AB}{}^2}{556150}+1.365 \tag{11}$$

The relationship between angle γ and angle θ is:

$$\theta=139°-\gamma=139°-(\arcsin\frac{1554029-l_{AB}{}^2}{556150}+1.365)\times 57.3° \tag{12}$$

4 Production test

4.1 Test time and place

Test was carried out in May 2014 in the demonstration area for paddy field of Academy of Agricultural Sciences of Harbin in China. Test area covered 50 m × 50 m. The soil type was black clay and the height of the stubble was no more than 15 cm. Its bulk density was 0.49 kg/m^2 and average soil firmness was 246 kPa (≤30 cm). The test was conducted within 2 d after steeped[27,28].

4.2 Test equipment

The test equipment included a Foton Lovol TA754E Tractor, an electronic balance, a soil firmness measuring instrument (TJSD-750 made in Yuanda Company of China), a tillage depth ruler, a measure tape, a measure cup and several other tools.

4.3 Test method

According to the agronomic requirements, the working speed (v), the puddle depth (h) and the angle of the flat shovel (θ) were selected as the influence factors.

On the basis of the preliminary pre-tests and further studied the influence of combining various factors on flatness[29], the program of the test using quadratic orthogonal-rotation combination design of three factors and five levels was selected. (Coding list of factor level was shown in Table 2).

Table 2 Coding list of factor level

Coding value	factors		
	x_1	x_2	x_3
Upper asterisk arm (+1.682)	5	16	39
Upper level (+1)	4	14	36
Zero level (0)	3	12	33
Lower level (−1)	2	10	30
Lower asterisk arm (−1.682)	1	8	27

Notes: x_1 refers to the working speed, km/h; x_2 refers to the puddling depth, cm; x_3 refers to the angle of the flat shovel, (°).

4.4 Evaluation indicators

According to the relative requirements of GB/T 24685-2009[30], the flatness and slurry were selected as the response indicators in the test.

4.4.1 Flatness

After two hours of working, 22 points were measured along working forward direction in the test area and the vertical distance between the surface and horizontal datum after puddling. The standard deviation of the vertical distance was flatness, which could be calculated from Equation (13):

$$S=\sqrt{\sum(Y-\overline{Y})/(n-1)} \tag{13}$$

where, $\overline{Y}$ is average vertical distance between the surface and horizontal datum after puddling, cm; Y is vertical distance between the surface and horizontal datum after puddling in measuring point, cm; S is flatness after puddling, cm.

4.4.2 Slurry

According to the diagonal method, slurry degree, which is the ratio between volume and weight of the sample, could be calculated by Equation (14).

$$E = \frac{W}{1000 \times V} \tag{14}$$

where, E is slurry degree, g/cm^3; V is volume of the sample, cm^3; W is weight of the sample, kg.

5 Results and analysis

5.1 Test results

Taking the factor level code value as an independent variable and flatness (y_1) and slurry (y_2) as response indicators, program and result of the test are shown in Table 3.

Table 3 Program and results of the test with quadratic orthogonal-rotation combination design

Test number	Factors			Response indicators	
	X_1	X_2	X_3	y_1	y_2
1	−1	−1	−1	3.90	1.14
2	1	−1	−1	4.10	1.20
3	−1	1	−1	3.70	1.05
4	1	1	−1	4.00	1.17
5	−1	−1	1	4.40	1.27
6	1	−1	1	4.70	1.38
7	−1	1	1	3.70	1.10
8	1	1	1	4.50	1.28
9	−1.682	0	0	3.70	1.10
10	1.682	0	0	4.40	1.27
11	0	−1.682	0	4.40	1.27
12	0	1.682	0	3.80	1.10
13	0	0	−1.682	4.10	1.19
14	0	0	1.682	4.60	1.33

5.2 Analysis of test result

5.2.1 Influence of working speed, puddling depth and angle of flatting shovel on flatness

By making a variance analysis (Table 4) and quadratic multivariate regression fitting of y_1, test result showed that removing the items had small influence on the response indicator. The quadratic multivariate regression equation of the independent variable is:

$$\begin{aligned} y_1 = 4.17 + 0.20x_1 - 0.16x_2 + 0.18x_3 - 0.057x_1^2 + \\ 0.049x_3^2 + 0.075x_1x_2 + 0.075x_1x_3 - 0.075x_2x_3 \end{aligned} \tag{15}$$

Table 4 Influence of each factor on flatness

Variance source	Quadratic sum	Degree of freedom	Mean sum of square	F	p
model	1.61	9	0.18	35.37	<0.0001
x_1	0.56	1	0.56	111.74	<0.0001
x_2	0.36	1	0.36	70.70	<0.0001
x_3	0.44	1	0.44	86.31	<0.0001
x_1^2	0.052	1	0.052	10.38	0.0067
x_2^2	0.025	1	0.025	4.98	0.0439
x_3^2	0.038	1	0.038	7.43	0.0173
x_1x_2	0.045	1	0.045	8.90	0.0160
x_1x_3	0.045	1	0.045	8.90	0.0106
x_2x_3	0.045	1	0.045	8.90	0.0106
Lack of fit	0.037	5	0.007364	2.04	0.1768
Pure error	0.029	8	0.003611		
Total sum	1.67	22			
Determinate coefficient R^2				0.9608	
CV/%				1.71	
Adeq Precision				23.202	

The regression diagnostics showed that the determinate coefficient (R^2) was equal to 0.9608, and signal-to-noise ratio (Adeq Precision) was 23.202, indicating that fitting degree and credibility of the equation are high and can be used to predict y_1. CV (coefficient of variation) was equal to 1.71%, which shows high reliability of the test. From the result of variance analysis (Table 5), factors x_1, x_2, x_3 and x_1^2 had significant influence on y_1, and factors x_3^2, x_1x_2, x_1x_3 and x_2x_3 had significantly influence on y_1 when confidence level (α) was 0.05. The influence of the other factors was not significant. The order of the influence significance of the factors was x_1, x_3 and x_2.

5.2.2 Influence of working speed, puddling depth and angle of flatting shovel on slurry

By making a variance analysis (Table 3) and quadratic multivariate regression fitting (Table 5) of y_2, test result showed that removing the items had small influence on the response indicator. The quadratic multivariate regression equation of independent variable is:

$$\begin{aligned} y_2 = 1.19 + 0.055x_1 - 0.049x_2 + \\ 0.052x_3 + 0.017x_3^2 - 0.019x_2x_3 \end{aligned} \tag{16}$$

The regression diagnostics showed that determination coefficient (R^2) was equal to 0.9496, and signal-to-noise ratio (Adeq Precision) was 20.964, which indicated that fitting degree and credibility of the equation were high and can be used to predict y_2. CV was equal to 1.88%, indicating high reliability of the test. From the result of variance analysis (Table 6), factors x_1, x_2 and x_3 had significantly influences on y_2, and factors x_3^2 and x_2x_3 had significant influences on what confidence level (α) was 0.05. The influence of other factors was not significant. The order of the influence significance of the factors was x_1, x_2 and x_3.

Table 5 Variance analysis of influence of each factor on the specific gravity of paddy field slurry

Variance source	Quadratic sum	Degree of freedom	Mean sum of square	F	p
model	0.13	9	0.014	27.24	< 0.0001
x_1	0.042	1	0.042	81.61	< 0.0001
x_2	0.033	1	0.033	65.25	< 0.0001
x_3	0.036	1	0.036	71.08	< 0.0001
x_1^2	0.00148	1	0.00148	2.89	0.1129
x_2^2	0.00148	1	0.00148	2.89	0.1129
x_3^2	0.00452	1	0.00452	8.81	0.0109
x_1x_2	0.00211	1	0.00211	4.12	0.0633
x_1x_3	0.00151	1	0.00151	2.95	0.1096
x_2x_3	0.00281	1	0.00281	5.49	0.0357
Lack of fit	0.00164	5	0.00033	0.52	0.7534
Pure error	0.00502	8	0.00063		
Total sum	0.13	22			
Determinate coefficient R^2				0.9496	
CV/%				1.88	
Adeq Precision				20.964	

5.3 Surface analysis of flatness response

According to the requirements of flat for paddy field, the range of y_2 was determined from 1-1.10 g/m^3 to avoid fragmented soil structure which may cause soil compaction phenomenon. Within this range, the lower, the better. Therefore, based on response surface methodology, the influence of all factors on y_1 was analyzed by fixing one of the three factors at zero and investigating the influence of the other two factors on y_1.

5.3.1 Influence of working speed and puddling depth on flatness

Fixing x_3 at zero (33°), the equation of x_1, x_2 is

$$y_1 = 4.22 + 0.20x_1 - 0.16x_2 - 0.058x_1^2 - 0.040x_2^2 + 0.075x_1x_2 \tag{17}$$

From Figure 7, the minimum value of y_1 was 3.7 cm, and y_1 increased with the increase of x_1 and decreased with the increase of x_2. In the two-factor interactions under the test level, x_1 had more significant influence on y_1 than x_2.

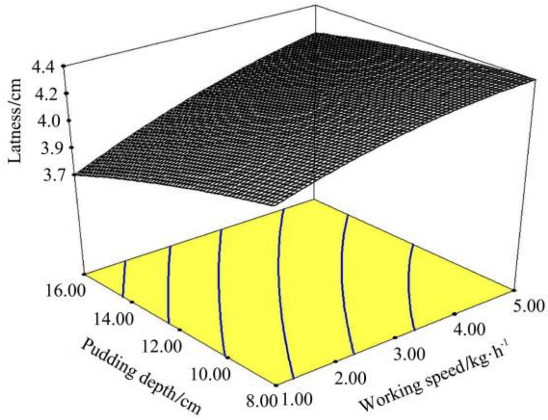


Figure 7 Influence of working speed and puddling depth on flatness

5.3.2 Influence of working speed and angle of flatting shovel on flatness

Fixing x_2 at zero (12 cm), we had equation of x_1 , x_3,

$$y_1 = 4.17 + 0.20x_1 + 0.18x_3 - 0.057x_1^2 + 0.049x_3^2 + 0.075x_1x_3 \tag{18}$$

From Figure 8, the minimum value of y_1 was 3.8 cm, and y_1 increased with the increase of x_1 and x_3. In the two-factor interactions under the test level, x_1 had more significant influence on y_1 than x_3.

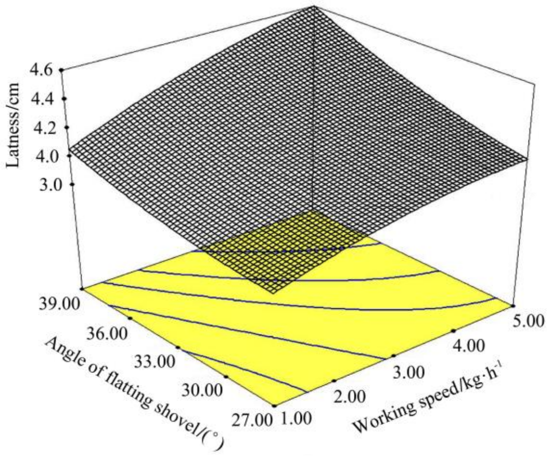


Figure 8 Influence of working speed and angle of flatting shovel on flatness

5.3.3 Influence of puddling depth and angle of flatting shovel on flatness

Fixing x_1 at zero (3 km/h), y_1 can be expressed as

$$y_1 = 4.16 - 0.16x_2 + 0.18x_3 - 0.039x_2^2 + 0.049x_3^2 - 0.075x_2x_3 \tag{19}$$

From Figure 9, the minimum value of y_1 was 3.9 cm, and y_1 decreased with the increase of x_2 and increased with the increase of x_3. In the two-factor interactions under the test level, x_3 had more significant influence on y_1 than x_2.

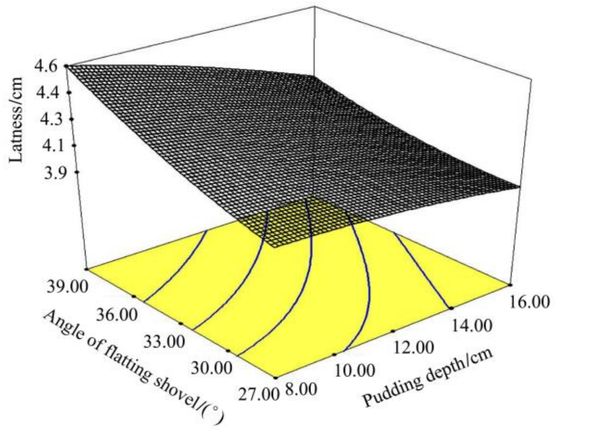


Figure 9 Influence of puddling depth and angle of flatting shovel on flatness

5.4 Parameter optimization

Based on the analysis of test results and model fitting[17-20] and considering the function requirements of flat and puddling, optimal combination of parameters program with the objective of the regression equation of flatness was obtained using the main objective function method and MATLAB software under the condition of slurry within the range of 1-1.10 g/m^3.

The optimal combination of parameters program was under the condition of working speed 1.05 km/h, puddling depth 16 cm, and angle of flat shovel 31.30°, then slurry degree was 1.03 g/m^3 and flatness was 3.7 cm in the moment.

5.5 Test verification

Taking the best combination of the above optimizing parameters[31-33], a different area in the same field was selected to take the test verification[34]. In order to avoid the random error, the measured value of the tests was averaged with ten replications. The verification result showed that the function indicators were slurry degrees at 1.06 g/m^3, and flatness at 3.7 cm. The results of verification were consistent with the results of software optimization and met design requirements[35, 36].

6 Conclusions

On the basis of this study, the following conclusions can be drawn.

1) The significance order of the influence factors on flatness and slurry was working speed, angle of flat shovel and puddling depth.

2) The optimal combination of operational parameters was under working speed is 1.05 km/h, puddling depth of 16 cm, and flat shovel angle is 31.30°, at this condition then slurry degree of 1.03 g/m^3 and flatness of 3.7 cm could be obtained. The verification test showed that the optimal combination of operational parameters could meet the agronomic requirements.

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[References]

[1] Li L H, Wang C, Zhang X Y, Zhang W. Improvement and optimization of preparation process of seedling-growing bowl tray made of paddy straw. Int J Agric & Biol Eng, 2014; 7(4): 12–19.

[2] Xue X Y, Tu K, Qin W C, Li H L, Zhang Z H. Drift and deposition of ultra-low altitude and low volume application in paddy field. Int J Agric & Biol Eng, 2014; 7(4): 23–28.

[3] Liu G, Lin J H, Si Y S, Lu C Y, Zhang X L. Development and experiment on laser controlled leveling system. Transactions of the CSAM, 2006; 37(1): 71–74. (in Chinese with English abstract)

[4] Scarlett A J, Price J S, Stayner R M. Whole-body vibration: evaluation of emission and exposure levels arising from agricultural tractors. Journal of Terramechanics, 2007; 44(1): 65–73.

[5] Xu D, Li Y N, Li F X, He H J, Zhao J K Study on combination of conventional and Laser-controlled land grading procedures. Journal of Hydraulic Engineering, 1999; 30(10): 52–56. (in Chinese with English abstract)

[6] Jacob Jeremiah Towa, Guo Xiangping. Effects of irrigation and weed-control methods on growth of weed and rice. Int J Agric & Biol Eng, 2104; 7(5): 22–33.

[7] Zhang T, Xia J F, Wu G, Zhang T Y. Automatic navigation path detection method for tillage machines working on high crop stubble fields based on machine vision. Int J Agric & Biol Eng, 2014; 7(4): 29–37.

[8] Langer T H, Ebbesen M K, Kordestani A. Experimental analysis of occupational whole-body vibration exposure of agricultural tractor with large square baler. International Journal of Industrial Ergonomics, 2015; 47: 79–83.

[9] Jiao S J. New technology and development situation of grader. Road Machinery and Construction Mechanization, 2008; 25(3): 10–17. (in Chinese with English abstract)

[10] Xu R Z, Wei Z M, Xia Y H, Tian Z X, Shi X S. Effect of laser precision land leveling on border irrigation and its water saving performance. Journal of Irrigation and Drainage,

2012; 31(2): 6–9. (in Chinese with English abstract)

[11] Chen J M, Zhao Z X, Chen J Q, Zhang Y. Design of nonlinear leveling control system for paddy leveler. Transactions of the CSAM, 2014; 45(7): 79–84. (in Chinese with English abstract)

[12] Tabatabaekoloor R, Yousefnia pasha H, Hashemi J. Comparison of efficiencies and costs of different weed controlmethods in paddy production in Iran. International Int J Agric & Biol Eng, 2012; 5(2): 28–33.

[13] Wang J F, Wang J W, Kong Y J, Yu H Z, Zhao D Y. Development and experiment of suspension ridger and its key components for paddy field. Transactions of the CSAE, 2013; 29(6): 28–34. (in Chinese with English abstract)

[14] Guo X P, Yuan J, Guo F, Fu Z L, Qi Q Z. Preliminary study on water-catching and controlled irrigation technology of rice. Transactions of the CSAE, 2009; 25(4): 70–73. (in Chinese with English abstract).

[15] Ren W T, Hu Z F, Cui H G, Li Q W, Zhang D F. Effect of laser-controlled land leveling and baby rice seedling direct planting on saving water. Transactions of the CSAE, 2003; 19(3): 72–75. (in Chinese with English abstract)

[16] Xiang C Y, Zhou D X, Song G, Gao X K. Research on permissive conversion limit of dry land to paddy field in Tonghe county, Heilongjiang Province. Transactions of the CSAE, 2012; 28(13): 226–230. (in Chinese with English abstract)

[17] Zhu S, Zhu Y. Effects of tyre inflation pressure and forward speed on vibration of an unsuspended tractor. Journal of Terramechanics, 2013; 50(3): 185–198.

[18] Bai G S, Du S N, Yu J, Ding Y P, Zhao Y. Laser land leveling improve distribution of soil moisture and soil salinity and enhance spring wheat yield. Transactions of the CSAE, 2013; 29(8): 125–134. (in Chinese with English abstract)

[19] Hou M L, Mao E R, Liu G. Study and test of the control technology for the laser-controlled land leveling system. Transactions of the CSAE, 2013; 29(8): 125–134. (in Chinese with English abstract)

[20] Zhou Y, Yu S S, Xia J F. Design and experiment of cultivator for high straw returning in paddy field. Transactions of the CSAM, 2012; 43(8): 46–49. (in Chinese with English abstract)

[21] Jiang M H, Sun S M, Han H Y. The design of 1DF-7760 multiple-small-tillage equipment. Journal of Agricultural Equipment & Technology, 2005; 3(2): 136–138. (in Chinese with English abstract)

[22] Cuong D M, Zhu S H, Ngoc N T. Study on the variation characteristics of vertical equivalent damping ratio of tire–soil system using semi-empirical model. Journal of Terramechanics, 2014; 51: 67–80.

[23] Malley D F, Mcclure C, Martin P D. Compositional analysis of cattlemanure during composting using a field portable near infrared spectrometer. Communications in Soil Science and Plant Analysis, 2005; 36(4): 455–476.

[24] Ren W T, Che Z, Liu J B. Experiment on effect of paddy mud on adhesion property of farm paper mulch. Transactions of the CSAE, 2011; 27(7): 129–133. (in Chinese with English abstract)

[25] Yang Z Q, Li J Q, Xu Y T. Research of data acquirement system for tiny soil adhesion. Journal of Huazhong Agricultural University, 2005; (4): 114–117. (in Chinese with English abstract)

[26] Zhang L, Ren L Q, Tong J, Zhao W J, Liu W. Study of soil-solid adhesion by grey system theory. Progress in Natural Science, 2004; 14(2): 119–124.

[27] Wang Z S, Xia J F, Xu Q C, Qiao X D. Power consumption testing system of high stubble buried device in paddy field. Transactions of the CSAE, 2011; 27(2): 119–123. (in Chinese with English abstract)

[28] Zhang C F, Huang H W, Tang Z J. Application of wireless LAN technology of consumed power measurement of cornstalk breaking. Transactions of the CSAM, 2008; 39(4): 125–127. (in Chinese with English abstract)

[29] Li Q, Lup X W, Wang M H, Zhang K F, Zhang Z P. Design of a laser land leveler for paddy field. Transactions of the CSAE, 2007; 23(4): 88–93. (in Chinese with English abstract)

[30] Ren W T, Che Z, Liu J B. Experiment on effect of paddy mud on adhesion property of farm paper mulch. Transactions of the CSAE, 2011; 27(7): 129–133. (in Chinese with English abstract)

[31] Hu L, Luo X W, Zhao Z X. Evaluation of leveling performance for laser-controlled leveling machine in paddy field based on ultrasonic sensors. Transactions of the CSAM, 2009; 40(Supp.): 73–76, 81. (in Chinese with English abstract)

[32] Li Q, Luo X W, Wang M H, Zhu S L, Hu Y J. Design of a laser land leveler for paddy field. Transactions of the CSAE, 2007; 23(4): 88–93. (in Chinese with English abstract)

[33] Zhao Z X, Luo X W, Li Q, Zhang L. Leveling control system of laser-controlled land leveler for paddy field based on MEMS inertial sensor fusion. Transactions of the CSAE, 2008; 24(6): 119–124. (in Chinese with English abstract)

[34] Hou L, Pan Y J, Wang Q L. Dynamic simulation on multi-drive system work device of grader. Journal of Xiamen University, 2011; 50(1): 47–52. (in Chinese with English abstract)

[35] Miyoko W, Tomoko Y, Kazuyoshi S, Zhao X Y. Distribution of anammox bacteria in a free-water-surface constructed wetland with wild rice (*Zizania latifolia*). Ecological Engineering, 2015; 81: 165–172.

[36] Pan Y J, Hou L, Wang Q L. Forward displacement analysis on hybrid mechanism of work device of grader. Journal of Zhejiang University, 2011; 45(8): 1346–1351. (in Chinese with English abstract).