DEM SIMULATION AND EVALUATION OF WELL CELLAR MAKING PERFORMANCE OF OPENER WITH LARGE SOCKET

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大窝套小孔成穴器对井窖成穴性能的离散元仿真和评价

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ABSTRACT

Well cellar seedling transplanting can effectively avoid series of problems such as long recovery time and poor uniformity of seedlings caused by the server climate conditions outside. Well cellar making is quite difficult in the upland with low moisture content. An opener with large socket was newly designed for the well cellar making. The well cellar making process was simulated by means of discrete element method (DEM), and its verification was qualified by soil bin test, with a relative error 7.46%. Taking arc radius of the opener socket, rotation speed and penetration speed as control factors, and collapse rate of the cellar hole as evaluation index, the influence of control factors on the collapse rate and their significance were obtained by Box-Behnken Design (BBD) test and analysis of variance (ANOVA). A quadratic regression equation of collapse rate with control factors was established, and the optimal parameters of the control factors were obtained as arc radius 128 mm, rotation speed 380 r/min and penetration speed 0.15 m/s, with the minimum collapse rate 22.70%. The collapse rate of the newly designed well cellar opener decreased much compared to the traditional one.

摘要

井窖式移栽可有效避免气候条件引起的还苗期长、秧苗均匀性差等一系列问题，为改善土壤墒情较差时井窖成穴难的现状，本文提出了一种大窝套小孔成穴器。采用离散元法对井窖制作过程进行数值模拟并通过土槽试验验证，相对误差为7.46%。以成穴器的圆弧半径、转速和入土速度为试验因素，以孔穴垮塌率为评价指标，通过 Box-Behnken 试验和方差分析得出各因素对孔穴塌陷率的影响及其显著性。建立各因素与孔穴垮塌率的二次回归模型，得到的最优参数为圆弧半径128 mm、转速380 r/min、入土速度0.15 m/s，最小垮塌率为22.70%。与传统的井窖式成穴器相比，其垮塌率明显降低。

INTRODUCTION

Transplanting, as a crucial link of tobacco planting, has a great influence on the survival of tobacco seedlings and the final yield of tobacco leaves (*Zhang, P. C. et al, 2007*). Planting depth of tobacco seedlings can directly affect nutrient-taking during the whole growth process. Studies have shown that the well cellar transplanting can avoid a series of problems such as weak seedlings in the best transplanting period, long recovery time and poor uniformity of seedlings due to the severe climate conditions outside (*Jia, R.L. et al, 2013; Luo, H. B. et al, 2012*). At present, the well cellar making machine is mainly of the backpack type, the opener is composed of a cylinder and a cone, and local structures were added to improve the efficiency (*Yu, L. H. et al, 2018*). As the soil is loose and porous, it will be compressed and move along the axial direction and radial direction during the well cellar making process. Soil type, soil moisture content, structure and working parameters of the opener are the key factors affecting the quality of well cellar (*Yu, L. H. et al, 2018*). Loose soil is not conducive to forming for the traditional well cellar opener with low soil moisture (the moisture content is less than 11%) (*Liu, G. H. et al, 2018*), which is an urgent problem to be solved.

Accurate descriptions of soil-tool interaction would be a major step forward in agricultural machinery design, which can effectively reduce the design cycle and manufacturing cost. As the soil is granular and discontinuous, deformation and breakage will occur when it contacts with the tools (*Shmulevich. I., 2010*). Discrete element method (DEM) allows granular materials to be treated as a collection of particles with certain shape and mass (*Hu, G. M., 2010*), and it is widely used to simulate soil-tool interaction.

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Han C. J. et al (2019) applied DEM to simulate the hole-forming process of the opener of watermelon seedling transplanter. Then, the effects of the small-end diameter and the theoretical working depth on the hole-forming effect were discussed. *Ji Y.J. et al (2014)* used DEM to study the effect of the inclination angle of the opener on hole size and said that the working speed and soil moisture content will affect the hole-forming effect.

In this study, an opener with large socket was proposed based on the requirement of well cellar making for tobacco seedlings. A soil model was established within EDEM to explore the optimal parameters of the opener, the micro-behaviour of the soil, and the quantitative evaluation of performance of well cellar making. The aim was to reduce the design cycle of the machine and provide technical support for the improvement of the transplanters.

MATERIALS AND METHODS

Opener design and test platform

Design of opener with large socket

To improve the performance of well cellar making with low soil moisture content, an opener with large socket was proposed, as shown in Fig. 1a. Compared with the traditional well cellar opener (Fig. 1b), a large socket was formed in the loose soil layer and a small hole was formed in the compacted soil layer in view of the differences in compactness and moisture content at different soil layers. The large socket functioned as wind prevention and heat preservation, rain collection and drought resistance, as well as watering and fertilization.

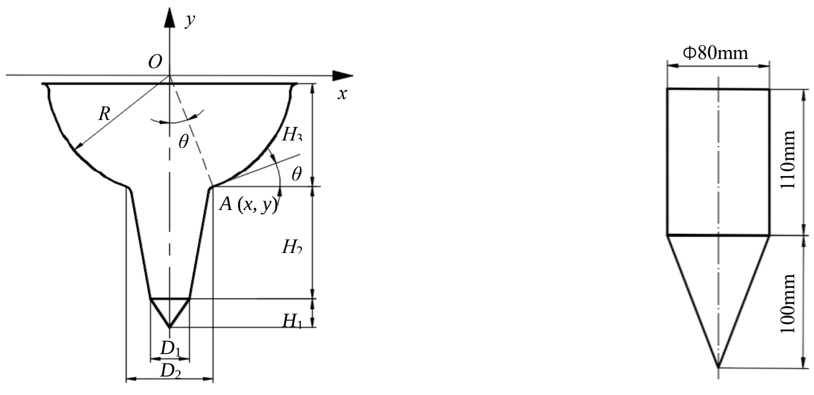
To help the tool penetration and ensure the uprightness of the seedlings, the bottom and the middle were designed to be conical, the diameter D_1 was 40 mm, and the height H_1 was 30 mm. Considering that the best well cellar specification for seedlings was circular with a diameter of 80-90 mm (*Luo, H. B. et al, 2012*), the diameter D_2 was 80 mm, and the height H_2 was 120 mm. Combined with agricultural requirements (*Chen, W. et al, 2015*), the height H_3 was 100 mm and the curve was an arc. A coordinate system was established with the centre of the circle as the origin. For any point A (x, y) on the arc, $x^2 + y^2 = R^2$ was satisfied. Then, the relationship between θ and R is expressed as:

$$\theta = \arctan\frac{x}{\sqrt{R^2 - x^2}}, \text{ [deg]} \quad (1)$$

Where:

θ is the angle of soil particle along tangent direction of the wall of the cellar hole, [degree].

According to the theoretical analysis, the smaller θ was, the smaller the tangent force was, and the less likely the particle slipped downward.



(a) Opener with a large socket (b) Traditional well cellar opener

Fig. 1 - Structure diagram

Test platform

In order to verify the working performance of the opener and the accuracy of the simulation, a test platform was designed, as shown in Fig. 2a. The test platform was mainly composed of lifting mechanism, power transmission mechanism, an opener with a large socket, soil bin, and rack, etc. The rotation speed and penetration speed of the opener can be adjusted to the specified values through speed control module. The basic dimensions of the soil bin were sides 600 mm and height 320 mm.

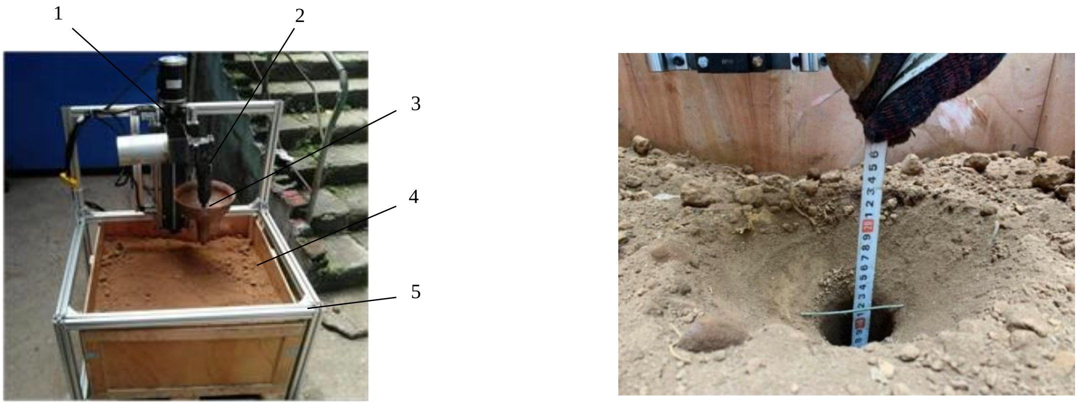
To ensure that the soil conditions in the soil bin were consistent with the field soil, a layered method was used to prepare soil (*Hang, C. G. et al, 2017*). As a result, the average moisture content of 0-120 mm (upper soil) and that of 120-320 mm (lower soil) soil layers were 7.6% and 12.8%, respectively.

The well cellar making performance has a significant effect on the growth of tobacco seedlings. For the well cellar made by the opener with large socket, large hole formed by the large socket was convenient for wind protection and water fertilization, the small hole of the lower part was used for seedling transplanting. In view of this effect, after the experiment was completed, the effective depth of the cellar hole was measured, which was the depth that was used for transplanting after soil particle slip, as shown in Fig. 2b, the collapse rate of cellar hole can be expressed as:

$$S = \frac{H - h}{H} \times 100\% \text{ , [\%]} \tag{2}$$

where:

S is the collapse rate, [%]; H is the theoretical transplanting depth (150 mm, i.e. H_1+H_2), [mm];
h is the effective transplanting depth, [mm].



(a) Test platform (b) Effective transplanting depth measurement

Fig. 2 - Soil bin test

1- lifting mechanism; 2 - power transmission mechanism; 3 - opener; 4 - soil bin; 5 - rack

Discrete element modeling

Properties of the materials

Establishing a correct model is an essential precondition for the accuracy of simulation results. It requires the use of contact models that can represent the characteristics of the materials as reliably as possible. Due to the deformation and the intermolecular forces between particles, Hertz-Mindlin (no slip) was defined as contact model between soil and machine, and Hertz-Mindlin with Johnson-Kendall-Roberts was defined as contact model between soil particles. The later contact model considers the cohesion between particles on the basis of Hertz contact theory. Even if particles are not in direct contact, there is attractive cohesion under this model, and the maximum cohesion of particles can be described as (*Johnson, K. L. et al,1971*):

$$F_{max} = -\frac{3}{2}\pi\gamma R^*, \text{ [N]} \tag{3}$$

where:

$F_{\max}$ is the maximum cohesion of particles, [N]; γ is the surface energy, [J/m^2];
R^* is the equivalent radius, [m].

Because moisture content differs at different soil layers, the cohesive strength between the soil particles and the ability to resist the movement of the soil particles are also different. Taking the soil of Weining tobacco area in Guizhou Province as the research object, in order to balance the calculation speed and simulation accuracy, sphere with particle radius of 2 mm was used to simulate soil particles in this study. The parameters involved in the simulation were shown in Table 1, which were mainly divided into the intrinsic parameters and the contact parameters. On the macroscopic scale, the repose angle of the material can reflect the flow and friction characteristics of the granular material, then coefficient of static friction, coefficient of rolling friction and surface energy of soil particles were calibrated by the repose angle test.

In this study, the lifting method (*Shi, L. R. et al, 2017*) was used to measure the repose angle. The soil was filled with a cylinder with diameter of 40 mm and height of 120 mm, then the cylinder was lifted at a speed of 0.02 m/s to form a cone-like pile on the plane. The simulation was carried out according to the physical test and the parameters was continually adjusted until the repose angle obtained by simulation was in accordance with the measured value. Then parameters of friction and surface energy of the soil particles were calibrated.

Table 1

Simulation parameters

Item	Top soil	Sub soil	Steel	Topsoil-topsoil	Topsoil-steel	Subsoil-subsoil	Subsoil-steel	Data source
Intrinsic parameters								
Density [kg/m^3]	1720	1870	7850	-	-	-	-	Measurement
Shear modulus [MPa]	10^6	10^6	7.9×10^{10}	-	-	-	-	*Fang, H. M. et al, 2016* *Yuan, Q. C. et al, 2018*
Poisson's ratio	0.38	0.38	0.3	-	-	-	-	
Contact parameters								
Coefficient of restitution	-	-	-	0.6	0.6	0.6	0.6	*Ucgul, M. et al, 2015*
Coefficient of static friction	-	-	-	0.45$^{(1)}$	0.5$^{(1)}$	0.6$^{(2)}$	0.6$^{(2)}$	$^{(1)}$ Calibration $^{(2)}$ *Fang, H. M. et al, 2016*
Coefficient of rolling friction	-	-	-	0.2$^{(1)}$	0.31$^{(1)}$	0.05$^{(2)}$	0.05$^{(2)}$	
Surface energy [J/m^2]	-	-	-	0.42	-	1.36	-	Calibration

Working model of an opener with large socket

Based on the soil contact model and parameters, a virtual soil bin of sides 600 mm and height 320 mm was built, in which the subsoil depth was 200 mm and the topsoil depth was 120 mm. To ensure the consistency of simulation and reality, soil particles were generated randomly and the sizes followed a normal distribution. The 3D model of an opener with large socket was established in Creo 3.0 and imported into EDEM. The simulation model was shown in Fig. 3. The opener moves down at a certain speed while rotating. In all simulations, the time step was 20% of Rayleigh time, and the grid cell size was $4R_{min}$, where R_{min} is the value of the minimum particle radius in the simulation.

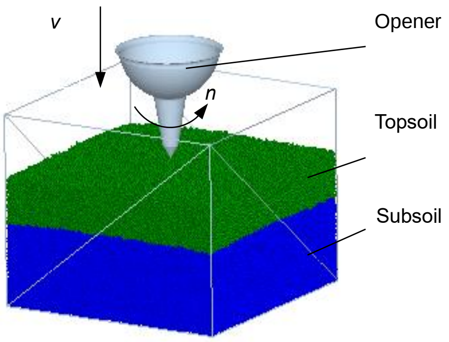


Fig. 3 - Virtual soil bin and geometric model of opener

Response surface optimization

The effects of main control factors on the performance of well cellar making were the opener's structure parameters and working parameters. Taking the arc radius (X_1), rotation speed (X_2) and penetration speed (X_3) as control factors and the collapse rate as the evaluation index, levels of control factors were determined according to Box-Behnken design (BBD), as shown in Table 2. And the detailed simulation experiment arrangement was shown in Table 3, with a total of 17 treatments, including 5 centre point repeated treatments. At last, a multiple quadratic regression equation was used to establish the functional relationship between control factors and the collapse rate.

Table 2

Control factors and levels

Level	Control factors		
	X_1 [mm]	X_2 [r/min]	X_3 [m/s]
-1	100	200	0.1
0	114	350	0.15
1	128	500	0.2

Table 3

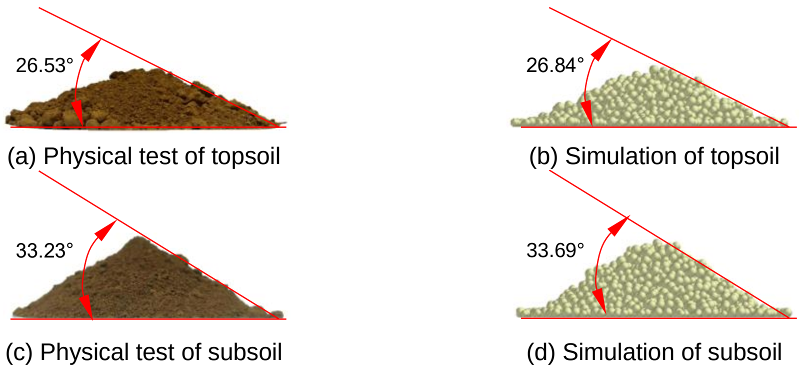
Experiment arrangement of BBD and results

Treatment	Level of control factors			collapse rate (%)
	X_1	X_2	X_3	
1	-1	-1	0	24.5
2	1	-1	0	34.8
3	-1	1	0	23.5
4	1	1	0	33.3
5	-1	0	-1	26.6
6	1	0	-1	36.2
7	-1	0	1	25.0
8	1	0	1	36.0
9	0	-1	-1	32.5
10	0	1	-1	31.7
11	0	-1	1	35.0
12	0	1	1	29.0
13	0	0	0	25.3
14	0	0	0	25.4
15	0	0	0	26.0
16	0	0	0	25.8
17	0	0	0	24.8

RESULTS

Soil model validation by repose angle test

The test results of topsoil and subsoil were shown in Fig. 4. Repose angles of the physical test and the simulation were measured in image process software of ImageJ. It could be seen that their outlines of repose angles were extremely similar, with relative errors of 1.17% and 1.38%, respectively. It indicated that the parameters of the soil model were accurate and reliable, which can be used for the optimization in this study. The parameter calibration results were shown in Table 1.



(a) Physical test of topsoil (b) Simulation of topsoil

(c) Physical test of subsoil (d) Simulation of subsoil

Fig. 4 - Repose angle

Statistics analysis

Regression model and analysis of variance

BBD experiment results of the collapse rate were obtained, as shown in Table 3. The regression analysis was applied to the experiment results with Design-Expert 8.0 and the regression equation, with a coefficient of determination R^2 0.9897, was obtained as:

$$S = 25.46 + 5.09X_1 - 1.16X_2 - 0.25X_3 - 0.13X_1X_2 + 0.35X_1X_3 - 1.30X_2X_3 + 1.23X_1^2 + 2.33X_2^2 + 4.26X_3^2 \quad (4)$$

The analysis of variance (ANOVA) result of quadratic polynomial model was shown in Table 4. According to ANOVA, arc radius of the opener (X_1) had the highest significant level of impact on the collapse rate of the cellar hole, and it was followed by rotation speed (X_2) and penetration speed (X_3), sequentially. Meanwhile, the interaction between X_2 and X_3 had an impact on the collapse rate1% probability level by F test of ANOVA. The P value of the regression model was less than 0.0001 and P value of the lack of fit was more than 0.05, showing that the regression model agreed with the experiment results.

Table 4

ANOVA of quadratic polynomial model

Source of variation	Quadratic sum	Degree of freedom	Mean square	F value	P value	Significance
Model	340.43	9	37.83	74.91	<0.0001	**
X_1	207.06	1	207.06	410.08	<0.0001	**
X_2	10.81	1	10.81	21.41	0.0024	**
X_3	0.50	1	0.50	0.99	0.3528	ns
X_1X_2	0.063	1	0.063	0.12	0.7353	ns
X_2X_3	6.76	1	6.76	13.39	0.0081	**
X_1X_3	0.49	1	0.49	0.97	0.3574	ns
X_1^2	6.40	1	6.40	12.67	0.0092	**
X_2^2	22.91	1	22.91	45.37	0.0003	**
X_3^2	76.32	1	6.32	151.15	<0.0001	**
Residual	3.53	7	0.50	-	-	
Lack of fit	2.66	3	0.89	4.07	0.1043	ns
Pure error	0.87	4	0.22	-	-	
Sum	343.96	16	-	-	-	

Notes: Significance:

*** means significant at 1% probability level by F test, ns means non-significant at 5% probability level.*

Parameter optimization

The response surface of collapse rate of the cellar hole as function of rotation speed (X_2) and penetration speed (X_3) was shown in Fig. 5. Control factor of X_2 was significant at 0.24% probability level by F test, and their interaction was at 0.1% probability level. As seen from response surface, with the increase of X_2 and X_3, the collapse rate decreased at first and then increased. While X_3 was close to 0.15 m/s, the collapse rate reached the minimum value. Control factor of arc radius (X_1) was significant at 0.1% probability level, and the collapse rate decreased while increasing X_1. Therefore, for the purpose of reducing the collapse rate, the optimized parameters were determined as: arc radius 128 mm, rotation speed 380 r/min and penetration speed 0.15 m/s. And the theoretical collapse rate of the cellar hole was 21.45% according to the regression equation.

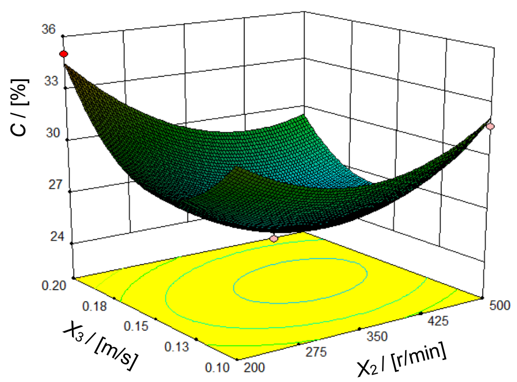


Fig. 5 - Response surface of collapse rate of the cellar hole as function of X_2 and X_3

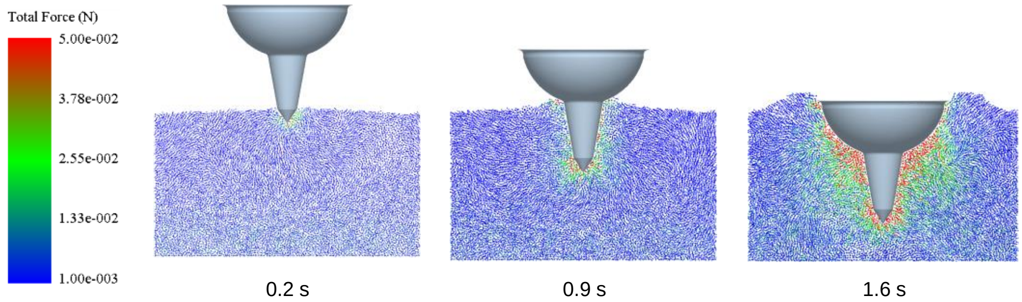
Comparative analysis

To verify the correctness of the optimization results and the advantages of the optimized opener, simulation test was carried out based on the optimized parameters, compared with that of the traditional well cellar opener.

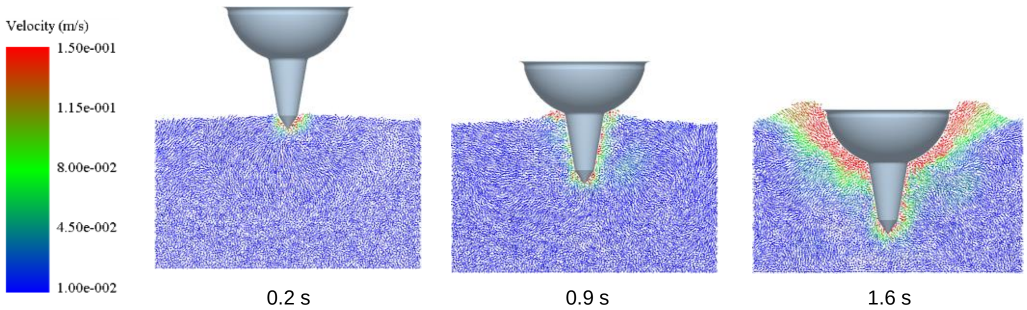
Well cellar making process

(1) Penetration process

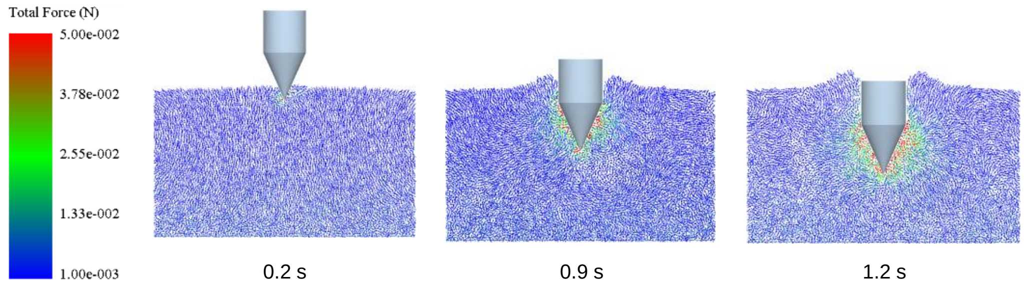
The force and velocity distributions of the soil in penetration process were shown in Fig. 5. As seen from Figs. 5a and 5b, when the optimized well cellar opener was just entering the soil (0.2 s), the tip exerted constant shear and compression on the soil, which made the soil particles in contact with the tool move sideways. As the opener moved downward, the disturbance of soil increased. When the arc was in contact with the soil (0.9 s), the soil moved along the normal direction of the arc under the compression, and the force was mainly concentrated on the tip of the opener. When the opener penetrated completely into the soil (1.6 s), the arc, especially the lower part, compressed the surrounding soil obviously. The particles of equal velocity were mainly distributed along the arc of the opener, and the particles closer to the arc had a higher velocity. Meanwhile, some particles moved along the tangential direction of the arc to the ground to form an uplift. In contrast, as shown in Figs. 5c and 5d, the force and velocity of soil particles were distributed along the conical wall during the operation of the traditional well cellar making, and the cylindrical wall basically did not exert longitudinal compression on the surrounding soil.



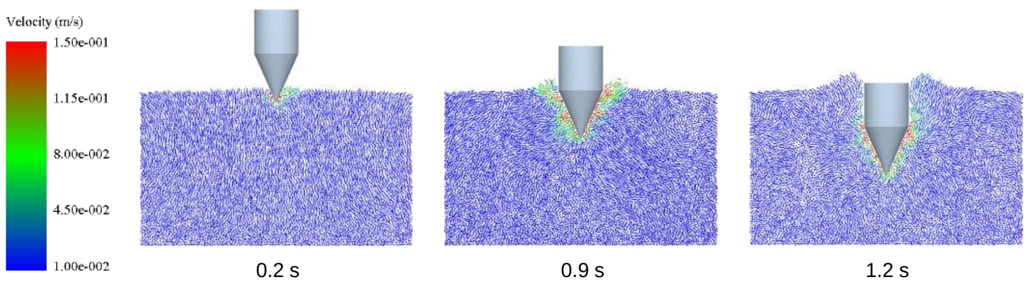
(a) Soil force distribution of the optimized well cellar opener



(b) Soil velocity distribution of the optimized well cellar opener



(c) Soil force distribution of the traditional well cellar opener

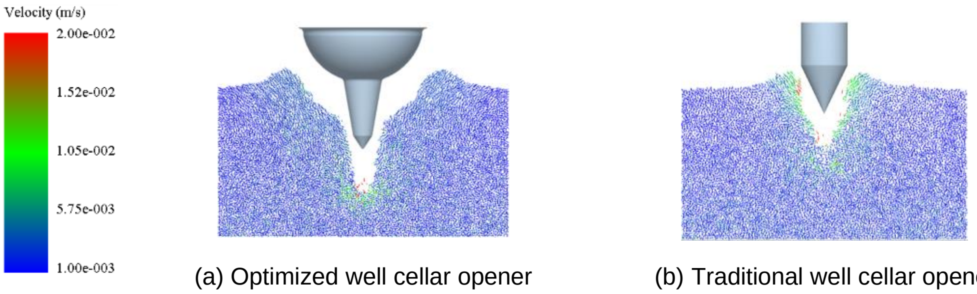


(d) Soil velocity distribution of the traditional well cellar opener

Fig. 5 –Soil force and velocity distribution at different time in penetration process

(2) Retraction process

The soil velocity distribution during retraction process were shown in Fig. 6. The soil velocity of the cellar hole formed by the optimized well cellar opener was lower than the traditional one and the particles moved along the tangential direction of the wall. While the soil velocity of the cellar hole formed by the traditional well cellar opener, especially that close to ground, was quite higher, and the particle moved toward the centre of the cellar hole, which was due to the fact that there was no longitudinal compression on the topsoil when the traditional well cellar opener was introduced into the soil. Under the action of gravity, the force chain between particles was more likely to be destroyed, thus it caused the soil to slip downward with a higher speed.



(a) Optimized well cellar opener (b) Traditional well cellar opener

Fig. 6 - Soil velocity distribution in retraction process

Quality of well cellar making

When the well cellar openers were completely removed from soil, part of the soil slipped downward to fill the cellar holes under action of gravity, as shown in Fig. 7. The red curve was the slide track of soil particles. The quality of the optimized well cellar opener was better and the upper layer of soil basically did not slide, with the collapse rate of 22.70%, while the cellar hole formed by the traditional well cellar opener was almost filled with the topsoil, and the collapse rate was as high as 63.20%. It is to be mentioned that compared with the theoretical value, the error of the simulation value of the optimized well cellar opener was 5.83%, indicating that the regression equation was correct.

(a) Optimized well cellar opener (b) Traditional well cellar opener

Fig. 7 - Quality of well cellar making

Soil bin test verification

The optimized well cellar opener was obtained and the soil bin test was carried out on the test platform. The experiment was repeated for 5 times, and the average value was taken as the reference value of collapse rate. The results showed that the average effective transplant depth of the holes was 113.2 mm, collapse rate was 24.53%, standard deviation was 0.79 mm, and the relative error between the soil bin test and simulation test was 7.46%. The errors were mainly due to the complex soil conditions, the influence of soil bin boundary and the vibration of the mechanical structure. The results of the soil bin test and the simulation test had good consistence.

CONCLUSIONS

In this study, a well cellar opener with a large socket was proposed. Well cellar making simulation and parameter optimization of the opener with a large socket were conducted. Main conclusions were drawn as follows:

- DEM is an effective way to animate interaction between the opener and the soil, and as a result, soil particle disturbance and quantitative evaluation of well cellar making can be obtained. The correctness of the simulation model was verified by repose angle and soil bin test.

- By statistical analysis of BBD test results, arc radius of the opener had the highest significant level of impact on the collapse rate of the cellar hole, and it was followed by rotation speed and penetration speed, sequentially. The optimized parameters of the opener were arc radius 128 mm, rotation speed 380 r/min, penetration speed 0.15 m/s.

- Compared with the traditional well cellar opener, the arc of the optimized well cellar opener had a remarkable compaction effect on the soil, and performance of well cellar making was improved significantly. The collapse rate had been greatly reduced from 63.20% to 22.70%.

ACKNOWLEDGEMENTS

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