ANALYSIS OF SOIL STRESS VARIATIONS DURING THE SEEDLING PLANTING PROCESS WITH DIRECT INSERTION SEEDLING DEVICE
/
直插式栽苗器栽苗过程中土壤应力变化过程分析

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DOI: https://doi.org/10.35633/inmateh-75-18

***Keywords:** Greenhouse transplantation, Seedling planter, Contact stress distribution, Peak resistance*

ABSTRACT
To explore the change law of contact stress distribution in the process of planting seedlings, the greenhouse transplanting equipment was developed to reduce labor intensity and improve the mechanization level of facility horticulture. This paper takes the direct insertion seedling planter as the research object, adopts the pressure distribution measurement system to study the soil stress distribution rule of different cross-section, digging depth and types of seedling planter. Both horizontal and longitudinal sections were obtained to show an increasing and then decreasing trend. The stress distribution is basically consistent at different digging depths, and the peak contact stress is roughly located at the center position. With the increasing of digging depths, the soil disturbance increases by the seedling planter and the hole tray seedlings, and the peak contact stress also shows a gradually increasing trend, leading to a gradual increase in the peak resistance of the seedling planter. The peak contact stress of the four opening seedling plant was higher than that of the three opening seedling plant. The main reason was that the soil disturbance of the four opening seedling plant increased, the peak contact stress distribution increased, and the peak resistance also increased. This study provides a basis for designing the greenhouse transplanters.

摘要
为探明栽苗过程中接触应力分布变化规律，研制温室移栽机具，降低劳动强度，提高设施园艺机械化水平。本文以直插式栽苗器为研究对象，采用压力分布测量系统研究了不同截面、不同入土深度和不同类型栽苗器的接触界面土壤应力分布变化规律。通过分析不同截面土壤应力的变化规律，得出横向截面和纵向截面均是呈现先增加后减小的趋势。不同入土深度下接触应力分布基本一致，接触应力峰值大致位于中心位置。随着入土深度的逐渐增加，栽苗器、穴盘苗对接触界面土壤的扰动增加，高应力区域占比逐渐增大，接触应力峰值也呈现逐渐增加的趋势，导致栽苗器的峰值阻力也呈现逐渐增大的趋势。四开口栽苗器的峰值接触应力大于三开口的栽苗器，主要原因是由于栽苗过程中四开口栽苗器的土壤扰动量增加，峰值接触应力分布增大，导致峰值阻力也增大。该研究为温室移栽机具的设计提供参考。

INTRODUCTION
Seedling transplantation technology is beneficial for mitigating the impact of seasons on crops, making full use of light and heat resources, improving land use efficiency, and increasing the index of multiple cropping. With the development of seedling transplanting technology, the demand for automated greenhouse transplanting equipment is also increasing *(Khadatkar et al., 2018; Jiang. 2017; Zhao et al., 2009)*.

At present, the change law of contact stress distribution during seedling planting is not clear, and the shape, size and operation parameters of seedling planter directly affect the contact stress distribution, and ultimately affect the planting quality. The research of greenhouse plant-transplanter has been reported abroad, mainly focusing on the effects of different seedling claws on transplantation efficiency and adaptability. These studies provide guidance for the development of greenhouse transplantation equipment *(Kutz et al., 1987; Kutz. 1985; Paradkar et al., 2021; Ting et al., 1990)*.

Developed countries such as Japan, the United States, and Australia have developed greenhouse transplanting equipment, but its cost is high, the structure is complex, and the maintenance cost is high. It is not compatible with China's seedling cultivation technology and transplanting auxiliary operations, making it difficult to adapt to the Chinese market *(Brewer et al., 1994; Choi et al., 2002; Simonton et al., 1991; Rahul et al., 2019)*.

In recent years, domestic scholars have also strengthened their research on greenhouse transplanting equipment. For example, *Zhou et al., (2009)*, designed an oblique wedge lever end effector, with a transplanting success rate of 76.11%. It designed a light and simple automatic transplanting machine, using two fingers and four pins to take seedlings, and transplanting experiments on 72 and 128 hole trays, respectively. The transplanting efficiency reached 1025 and 1221 plants/h, respectively, and the average transplanting success rate was 90.7% (*Han et al., 2016; Han et al., 2015*).

Cui et al., (2022), designed an adjustable seedling end effector based on cylindrical cam, which can adapt to various transplanting operations with different spacing between hole trays. The success rate of transplanting is 93.33%, and the transplanting efficiency is 22 plants/min.

Tian et al., (2010), designed a transplanting machine with four rows of seedling claws. The transplanting efficiency is 1800-2400 plants/h, and the transplanting success rate is 81.2%.

Yu et al., (2023), designed an 8-row synchronous seedling picking mechanism with a success rate of 95% for transplantation.

Meng. 2021, developed a small space secondary clamping claw for taking seedlings, the average efficiency of transplanting was 4320 plants/h, and the success rate of transplanting could reach 97.22%.

Zhang et al., (2023), designed a seedling end effector based on the principle of top clamp seedling picking, and achieved a success rate of 93.25% in seedling feeding. The pot has good integrity and meets the requirements for automatic transplanting and seedling retrieval of leafy vegetables in dry land.

In order to improve the mechanization level of facility horticulture, it is also urgent to study the change law of seedling planter, hole tray seedling and soil during the seedling planting process. Therefore, it is of great significance to study the change law of contact stress distribution in planting process to reduce planting resistance and improve planting efficiency.

The direct insertion seedling planter can quickly complete the planting of the hole tray seedlings and reduce the labor intensity. During the seedling planting process, there is an impact load between the seedling planter, hole tray seedlings, and the soil. Different soil physical properties, the structural parameters of the seedling planter, and specifications of the hole tray seedlings can affect the distribution of contact stress. It is difficult for the contact stress of soil in the theoretical state to accurately describe the stress in the complex field environment. The pressure distribution measurement system developed by the Tekscan in the United States is widely used to detect contact points and areas, contact interface shapes, and contact stresses (*Komarnicki et al., 2017; Stopa et al., 2018*). In this paper, the pressure distribution measuring system was used to carry out transplanting experiment with the direct insertion seedling plant, and the change law of soil stress distribution at the contact interface was studied under different factors. This study provides a basis for designing a greenhouse transplanter, reducing labor intensity, and improving the mechanization level of facility horticulture.

MATERIALS AND METHODS

Basic structure and motion analysis of the direct insertion seedling planter

The direct insertion seedling planter primarily consists of a tension spring, planting cylinder, pulling hook, and planting claw, as shown in Figure 1.

The planter has a height of 900 mm, a diameter of 76 mm. The planting claw opening is 140 mm in length. Its working principle involves the planting claw impacting the soil, while the puller drives the pulling hook to move the connecting ring upward. This motion causes the lower pulling hook to drive the planting claw, thereby facilitating the breakthrough of the soil. Once the seedling tray sinks to the bottom, the planting claw opens to release the seedling. The planter is then withdrawn, and the soil automatically backfills, completing the transplanting process.

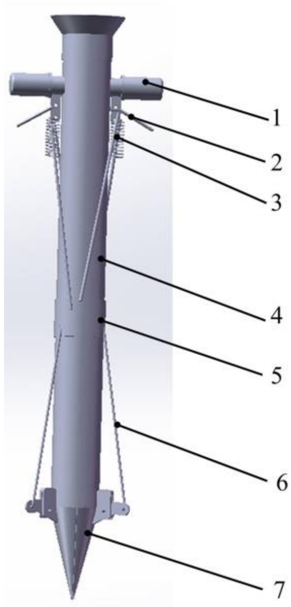

Fig. 1 – The 3D model of the direct insertion seedling planter.
1. Rubber handle. 2. Puller. 3. The tension spring. 4. Planting cylinder. 5. Connecting ring. 6. Pulling hook. 7. Planting Claw.

Sensor deployment

The pressure distribution measurement system primarily consists of the 3150 flexible thin-film network tactile pressure sensor, along with handles, computers, and other components. The core of the system is the 3150 flexible thin-film grid sensors, as shown in Figure 2. This sensor is based on a matrix that incorporates a large number of horizontal and longitudinal conductors, intersecting to form an array of stress-sensing points (*Hunston. 2002; Yang et al., 2018; Li. 2020*). The sensing area is 435.9 mm × 368.8 mm in length × width and 0.1 mm in thickness, with a thickness of 0.1 mm. The sampling frequency of the sensor is 0~100 Hz.

Fig. 2 - 3150 Flexible thin-film network tactile pressure sensor

To ensure the testing system records accurate data, the sensor is first calibrated. As shown in Figure 3, the sensor was placed in the middle of the black rubber pad and the transparent plastic sheet (L×W×H of 470 mm × 450 mm × 1 mm) before the test started. An acrylic frame is then placed on top. Soil is added to the acrylic frame (L × W × H of 470 mm × 450 mm × 170 mm) above the measurement system and compacted. The sensors are zeroed in preparation for the planting test.

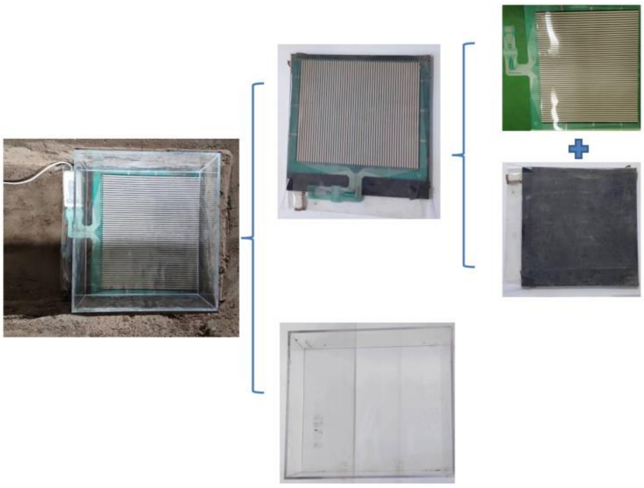

Fig. 3 - Installation of sensor

Test materials and equipment

The experiment was conducted in collaboration with Inner Mongolia Heyuan Agricultural Technology Co., Ltd., which cultivated 72 hole tray seedlings. The seedling substrate consisted of grass charcoal, vermiculite and perlite with a mass ratio of 3:1:1. The age of the seedlings was 30 d. The moisture content of the seedlings was measured between 58.78% and 62.47% using the DHG-9245A blower dryer. To study the soil stress distribution during the planting process of the direct insertion seedling planter, a contact stress distribution test bench was developed, as shown in Figure 4. The test stand mainly consists of a seedling planter, a pressure distribution measurement system, a computer and an acrylic frame. The test soil was a sandy loam and the measured soil moisture content ranged from 6.42% to 8.15%. The sensor needs to be calibrated before the test was started. The sensors were laid out in a fixed area, sieved for foreign matter such as clods and stones, and the completed sieved soil was filled into an acrylic frame and levelled off. Before testing, the sensor was calibrated, and sensors were laid out in a fixed area. The soil was sieved to remove foreign matter such as clods and stones, then filled into the acrylic frame and leveled. The sensor was zeroed before starting the test. At the end of the experiment, soil stress and pressure distribution data were retrieved from the I-Scan system. By analyzing the data at various moments and positions, the pressure distribution changes during the seedling planting process were examined. The soil compactness inside the acrylic frame was measured before each test, yielding values of 0-10 N/cm² at a depth of 100 mm.

Fig. 4 - Soil stress distribution test at the contact interface during seedling planting process.
(a) Sensor deployment; (b) Hole tray seedlings; (c) Different types of seedling planters

Test methods

This study investigates soil stress distribution during the seedling planting process by varying the soil depth within the acrylic frame and changing the type of seedling planter (three openings, four openings). Using a pressure distribution measurement system, peak contact stress and peak resistance pressure data were collected to analyze how soil stress distribution changes with different soil depths and planter types. The test factors and levels are shown in Table 1.

Table 1

Three axis dimensions of peanut seeds

Factors	Level 1	Level 2	Level 3
Digging depth[mm]	60	80	100
Type of seedling planter	Three openings		Four openings

RESULTS

Changing law of soil stress distribution in different cross sections during seedling planting process

The direct insertion seedling planter, configured with three openings and a 100 mm planting depth, was lowered at a constant speed during the planting test. A pressure distribution measurement system was used to monitor changes in soil stress at the contact interface. Low-stress areas are indicated by dark blue, high-stress areas by red, and areas with zero contact stress are colorless. Peak contact stress (Pmax) was obtained through the I-Scan system, with test results shown in Figure 5. When the soil depth of the seedling planter is 100 mm, its peak contact stress Pmax = 68 kPa. Due to the presence of a large number of horizontal and longitudinal conductors inside the sensor, it is necessary to analyze the changes in soil stress distribution during the seedling planting process in order to thoroughly study the changes in soil stress distribution at the horizontal and longitudinal sections. Both horizontal and longitudinal sections were obtained to show an increasing and then decreasing trend.

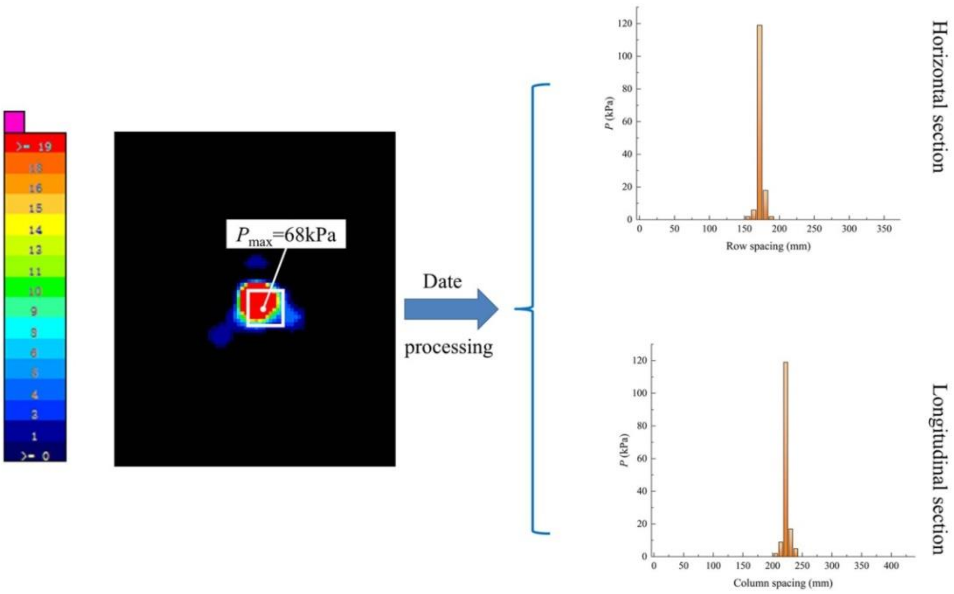

Fig. 5 - Variation of soil stress distribution in different cross sections

Effect of the contact stress distribution at different digging depths

The direct insertion seedling planter used in the experiment had three openings, with digging depths set to 60 mm, 80 mm, and 100 mm. The planter was lowered at a fixed rate during the planting tests. After the experiment, the data were processed using the I-Scan system, and the results are shown in Figure 6. The contact stress distribution remained largely consistent across different digging depths, with the peak contact stress (Pmax) generally occurring at the center.

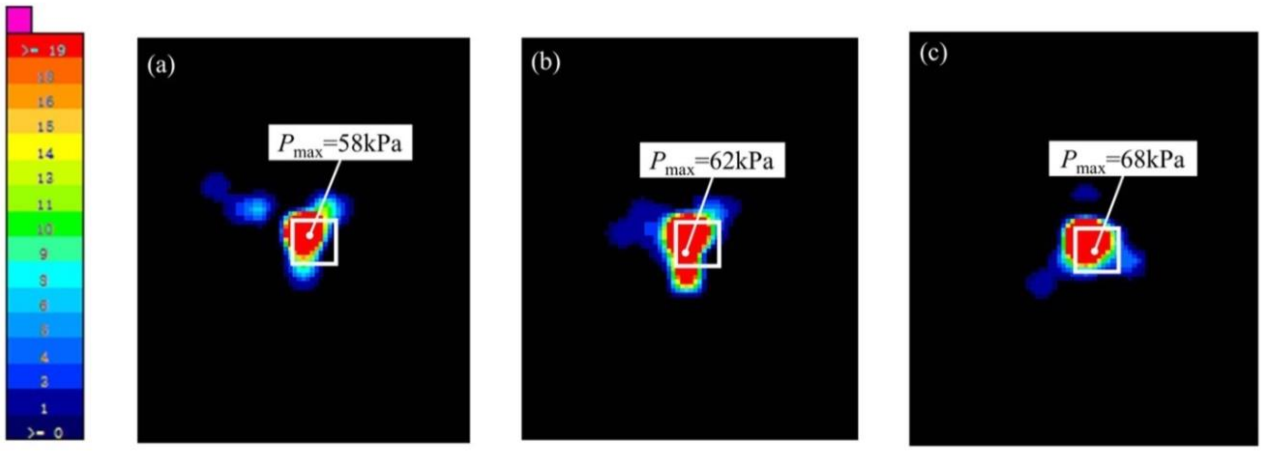

Fig. 6 - Variation of soil stress distribution at the digging depth. (a) Digging depth 60 mm; (b) Digging depth 80 mm; (c) Digging depth 100 mm

The direct insertion seedling planter compresses and shears the soil, causing soil particles to shift. At the same time, the planter experiences a reaction force from the soil, which represents the resistance encountered during planting. To further investigate the contact stress distribution, the variation in peak resistance at different digging depths was examined, as shown in Figure 7. As the digging depth of soil increases, the soil disturbance and the seedlings increases, the contact area gradually increases, and the peak resistance also shows a gradually increasing trend.

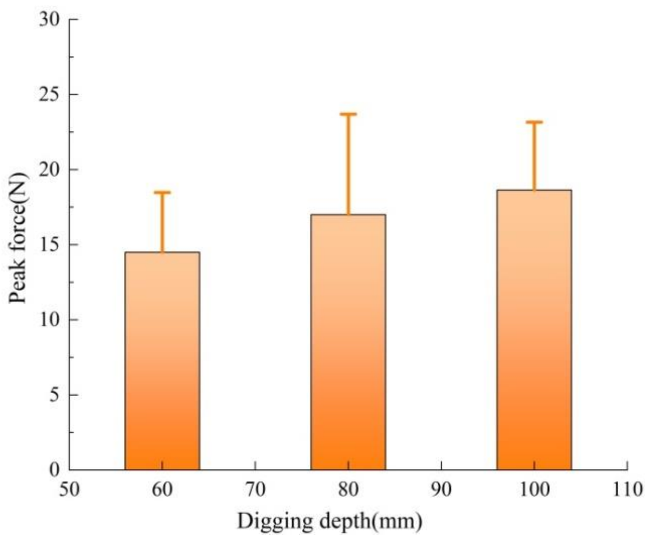

Fig. 7 - Variation changes of peak resistance at the digging depth.

Influence of contact stress distribution in different types of seedling planters

The digging depth of the direct insertion seedling planter is 80 mm, and the types of seedling planters are three or four openings. The planter is lowered at a fixed speed for seedling planting experiments. A pressure distribution measurement system was used to track changes in soil stress distribution. The experimental results are shown in Figure 8. The contact stress distribution in different types of seedling planters is basically consistent, and the peak contact stress (Pmax) is roughly located at the center, with high stress areas occupying the main area. The peak contact stress of the four opening seedling planter is greater than that of the three opening seedling planter. The main reason is that the four opening seedling planter has more planting claws than the three opening seedling planter, which increases the soil disturbance, leading to an increase in the distribution of peak contact stress.

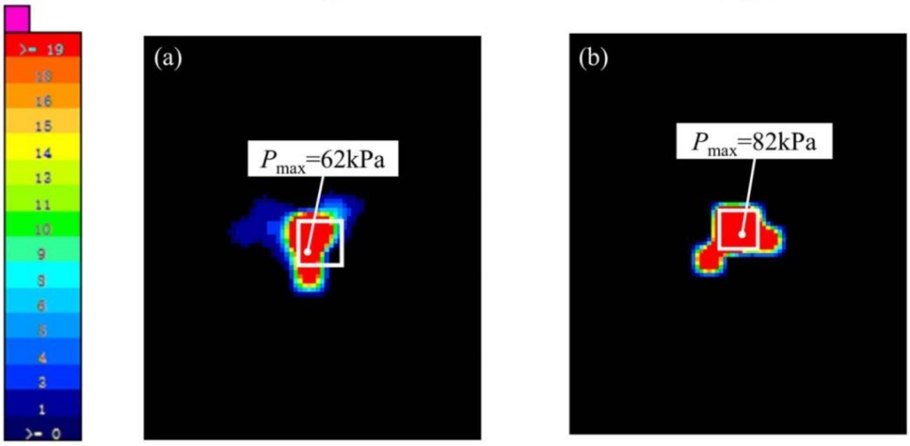

Fig. 8 - Variation of soil stress distribution in different types of seedling planters. (a) Seedling planter with three openings; (b) Seedling planter with four openings

To further study the contact stress distribution, it is necessary to study the variation of peak resistance of different types of seedling planters, as shown in Figure 9. The peak resistance of the four opening seedling planter is greater than that of the three opening seedling planter, mainly due to the increased soil disturbance caused by the four opening seedling planter during the seedling planting process, which increases the distribution of peak stress and leads to an increase in peak resistance.

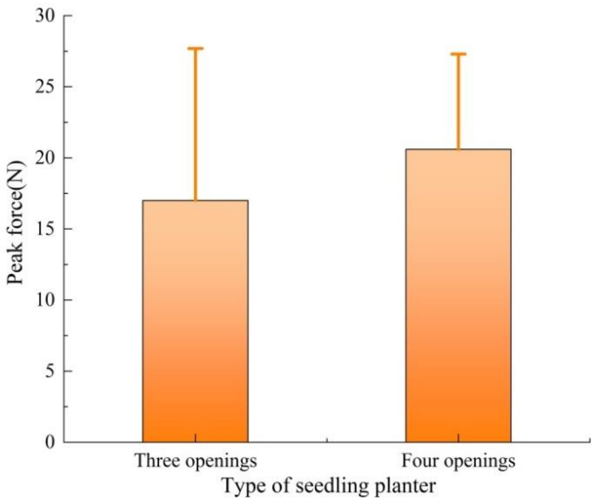

Fig. 9 - Variation changes of the peak resistance in different types of seedling planters

Discussion

This paper takes the direct insertion seedling planter as the research object, adopts the pressure distribution measurement system to study the soil stress distribution rule of different cross-section, digging depth and types of seedling planter. Both horizontal and longitudinal sections were obtained to show an increasing and then decreasing trend. The stress distribution is basically consistent at different digging depths, and the peak contact stress is roughly located at the center position. With the increasing of soil depth, the soil disturbance increases by the seedling planter and the hole tray seedlings, and the peak contact stress also shows a gradually increasing trend, leading to a gradual increase in the peak resistance of the seedling planter. The peak contact stress of the four opening seedling planter was higher than that of the three opening seedling planter. The main reason was that the soil disturbance of the four opening seedling planter increased, the peak contact stress distribution increased, and the peak resistance also increased. However, the labor intensity of the direct insertion seedling planter is still relatively high, and there are problems such as uneven depth during the actual seedling planting process, resulting in significant changes in the experimental data of soil stress distribution. Therefore, it is reasonable to choose the type of seedling planter and design the greenhouse direct insertion transplanter to reduce labor intensity and improve the mechanization level of facility horticulture.

CONCLUSIONS

This paper takes the direct insertion seedling planter as the research object, adopts the pressure distribution measurement system to study the soil stress distribution rule of different cross-section, digging depth and types of seedling planter. The main conclusions are as follows:

1）Both horizontal and longitudinal sections were obtained to show an increasing and then decreasing trend. The stress distribution is basically consistent at different digging depths, and the peak contact stress is roughly located at the center position. With the increasing of digging depth, the soil disturbance increases by the seedling planter and the hole tray seedlings, and the peak contact stress also shows a gradually increasing trend, leading to a gradual increase in the peak resistance of the seedling planter.

2）The peak contact stress of the four opening seedling planter was higher than that of the three opening seedling planter. The main reason was that the soil disturbance of the four opening seedling planter increased, the peak contact stress distribution increased, and the peak resistance also increased.

ACKNOWLEDGEMENT

This project was funded by National Natural Science Foundation of China (NSFC) (32160423) and Shandong Agriculture and Engineering University Start-Up Fund for Talented Scholars (2024GCCZR-05). We also appreciate the work of the editors and the reviewers of the paper.

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