EFFECT OF TINE GEOMETRY ON PENETRATION RESISTANCE DURING VERTICAL MOVEMENT ON NATURAL GRASSLAND
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典型刀齿类耕作部件的草地贯入试验研究

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ABSTRACT

Novel tillage tools causing minimizing surface vegetation deterioration are desired in degraded natural grassland mechanical restoration technology development. This paper attempted to study the effect of tine geometry in its vertical movement on penetration resistance. Four very narrow tines were defined (i.e. rectangle, triangle, crescent and mososeries) based on the geometry of the cutting edge, a special test unit was manufactured as well. Field experiments were conducted on natural grassland. The effects of tine geometry and contact surface area on soil penetration resistance were investigated and surface disturbance obtained. Results indicated that the tendencies of penetration resistance varied with the working depth or contact surface area, and showed differences between the four tines affected by different cutting-edge geometries. The crescent tine obtained the highest penetration resistance as compared to the others, and the mososeries tine got the lowest value. Penetration resistances of all the tines increased with the attack surface area with an exponential function (R^2≥0.94) or a power function (R^2≥0.95) respectively, depending on the penetration angle equalling 90° or being less than 90°, nonlinear tendency with penetration depth. It could be concluded that penetration resistance was influenced a lot by the tine geometry parameters such as contact surface area and penetration angle. The cutting edge of the tine with continuous acute penetration angle that could obtain lower resistance and stable force variation curve was more suitable for operation on natural grassland.

摘要

为探索适用于退化草地机械化改良作业的关键耕作部件，设计了 4 种不同形状的极窄刀齿，并搭建了试验台，进行草地贯入失效试验，重点对刀齿的贯入阻力进行分析。结果表明：刀齿贯入阻力随深度和接触面积的变化趋势受刀齿形状的影响而存在差异，新月形刀齿的贯入阻力最大，弦月形刀齿的最小，贯入阻力与贯入深度呈非线性正相关规律，与接触面积呈指数函数或幂函数变化规律（R2≥0.94）。刀齿刃口的入土角度和刀齿与土壤的接触面积均对贯入阻力产生影响，且贯入阻力变化程度受刃口的入土角度的影响，入土角度为直角时，贯入阻力存在急剧变化的阶段，入土角度为锐角时，贯入阻力变化相对稳定，宜选择刃口入土角度为连续锐角的刀齿进行作业。

INTRODUCTION

Tangled long strong *Leymus chinensis* (Trin.) Tzvel. (referred to as L-C hereafter) roots and soil formed soil-root composite structures underground on natural grassland, weakening the aeration and water permeability of the soil, accelerating the soil compaction and hardness, becoming one of the major reasons of natural grassland degradation in China *(You et al.,2011; He et al., 2016; Hamza et al., 2005)*. Using tillage tools to break the hardened soil-root composite structures on natural grassland that could improve the plant growth environment in the soil by improving the soil physical, chemical and biological properties, was verified to be one effective practice for the degraded natural grassland restoration *(Chen et al., 2017; Alvarez and Steinbach, 2009; Diabate et al., 2018; You et al., 2012)*.

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Common mechanical improvement methods included soil aerating, fertilization, shallow tillage, root cutting, soil loosening and reseeding etc. *(He et al., 2015; Sawtschuk et al., 2012; Bhogal et al., 2011)* have been applied for degraded natural grassland restoration in recent years.

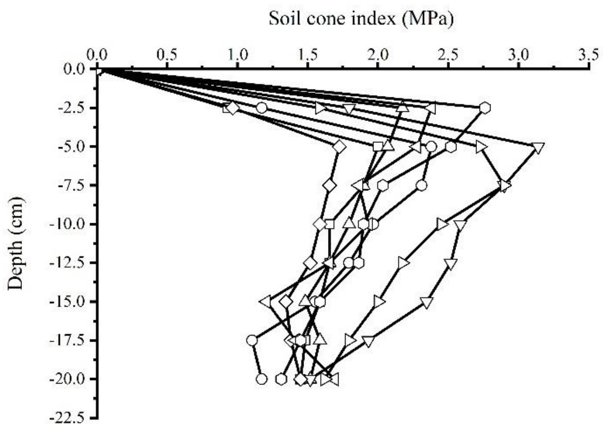
Novel low-disturbance tillage tools (e.g., rectangular tine, triangular tine, rotary blade, and crescent blade) for natural grassland continuously emerged due to problems such as soil nutrient loss and soil erosion brought about by over-turning soil clods, and large surface disturbance area created by conventional tillage tools *(Su et al., 2004; Lal R., 2007; Ramirez et al., 2019; You et al., 2017)*. Such tillage tools belong to narrow tines or very narrow tines because their working width is much smaller than the working depth *(Godwin and O'Dogherty, 2007)*. During operation, these tools will not create large-scale soil surface failures, the soil disturbance being relatively low. The movements can be divided into many combined processes with penetration and rotation. However, their geometry structure parameters affected the working resistances and working performance a lot. Few literatures on the soil-blade interactions, especially the penetration interaction have been found. The interaction relationships between tillage tools and soil layer on natural grassland still need to be investigated.

In order to further explore suitable tools and key components used for mechanized improvement of degraded grassland, this paper mainly investigated the effects of very narrow tine geometry on the penetration resistance and disturbance on natural grassland, providing theoretical reference and technical support for the design and optimization of the special tillage tines for degraded natural grassland restoration.

MATERIALS AND METHODS

- **Experiment site description**

The experiment site was located in typical natural grassland in Chabei district of Hebei province (41°28'31.649″N, 115°1'28.733″E). L-C was the dominant grass species of this area. A 12 m×12 m block was randomly selected as the experimental field site. Average bulk density, moisture content and porosity of the soil layer within the depth range of 0-20 cm on natural grassland were obtained based on the survey method as He et al. (2016) reported, ranging from 1.04 to 1.37 g/cm^3, from 9.19% to 16.68%, and from 48.32% to 60.63%, respectively. The L-C horizontal rhizomes mostly concentrated at the depth range of 5-6 cm underground, and were rarely distributed at the depth of more than 10 cm, as shown in Fig.1 (a). In the depth range of 0-10 cm underground, the tangled roots and soil formed soil-root composite structures underground. The soil cone index was measured using a hand-held cone penetrometer (SC 900, Spectrum Technologies, Inc.) with a small cone as described in ASAE standards S313.3 (2009). The value of soil cone index increased first and then decreased with the depth increasing, the maximum value was obtained at the depth range of about 5 cm. When the depth exceeded 10 cm, there was no big change about the soil cone index values. The soil cone index curves were as shown in Fig.1(b).



a) b)

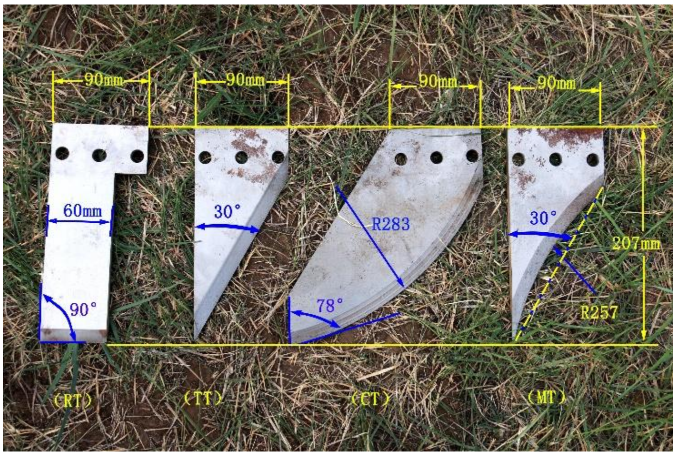
Fig. 1 - The L-C roots distribution underground and soil cone index curves

- **Experimental tines and test unit**

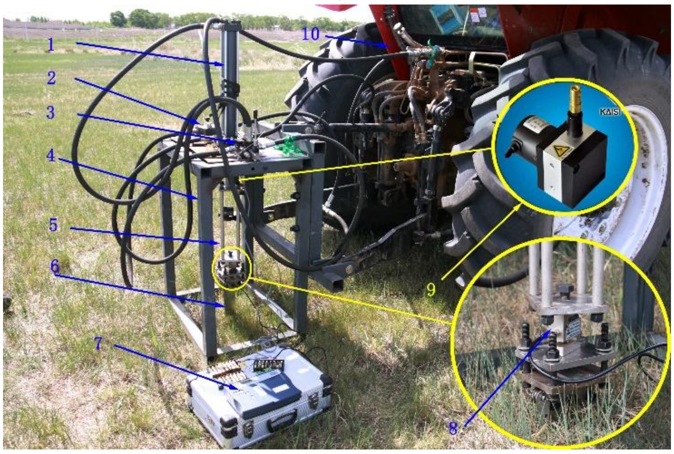
Four very narrow tines with different geometries were designed and applied in the experiments based on previous research reported by You (2011) and the tools applied on normal soil aeration machine, soil gashing and root cutting machine, and fertilizer injection machine. These tines were defined as rectangle tine (RT), triangle tine (TT), crescent tine (CT), and mososeries tine (MT), respectively, as shown in Fig.2 (a).

The thickness was 7 mm, and maximum value of the height was 207 mm. All tines were designed with a cutting edge with a cutting angle of 30 degrees, but different geometry curves. Three through holes with equal spaces were manufactured for mounting and fixing with the test unit.

A test unit was set up, mainly consisting of frames, a hydraulic cylinder, a reversing valve, a flow valve, a displacement sensor, a force sensor, a data acquisition unit (SQ 2020, Grant Squirrel) and hydraulic pipes etc., as shown in Fig.2 (b). The test unit was mounted with a tractor by a three-point linkage. The hydraulic cylinder, reversing valve and flow valve connected with the tractor hydraulic system through hydraulic pipes. The force sensor and displacement sensor were used for recording the resistance and displacement values of the tines during the penetration operations, respectively, and these values from the sensors were collected by the data acquisition unit.



a)



b)

Fig. 2 – Experimental tines and test unit

1- hydraulic cylinder; 2-flow valve; 3- reversing valve; 4-mounted frame; 5-support frame; 6-very narrow tine; 7- data acquisition unit; 8-force sensor; 9-displacement sensor; 10-tractor

- **Experimental procedure**

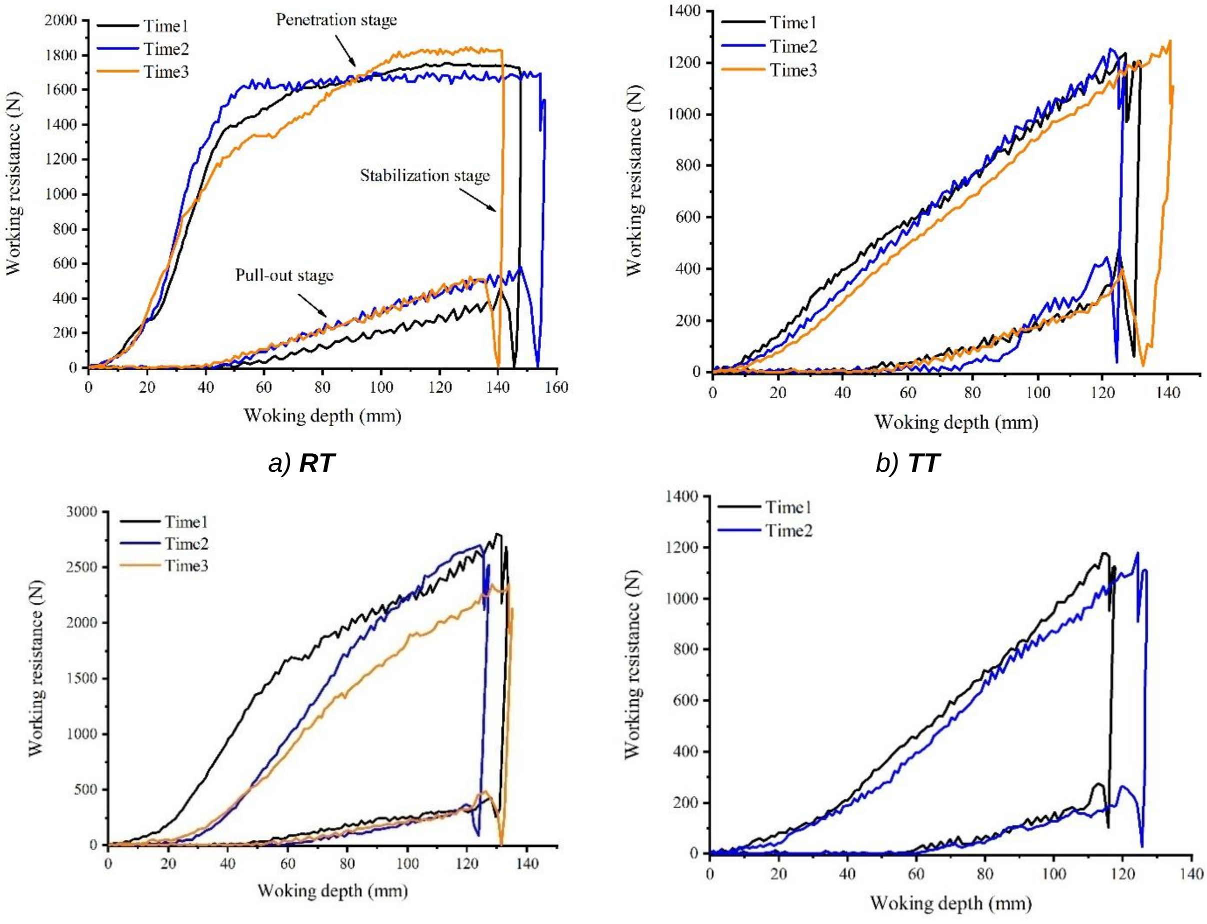
For all experiments, the very narrow tine was vertically inserted into the soil on natural grassland by operating the hydraulic system. The reversing valve and flow valve were used to control the movement and speed in the direction of penetration. When the tines reached the maximum effective working depth, then the reversing valve was controlled to change the moving direction of the tine until the tine was pulled back upon the soil surface. Via the hydraulic system and flow valve, the average penetration speed was controlled at 1.06±0.12 cm/s, the average pull-out speed was 1.50±0.04 cm/s. All penetration tests for each very narrow tine were replicated three times at different spots within the experiment field.

The force data from the force sensor was the real resistance of the tine during the penetration experiment; when the sensor was under pressure, the values were negative, and vice versa the values were positive. When the tine was inserted into the soil, the sensor was under pressure, when it was pulled out, the sensor was stretched. The influence of the weight coming from the tines and connecting parts had been eliminated in the experiments.

RESULTS

- **Effects of cutting edge geometry on working resistances during penetration operations**

The working resistance curves with working depth of the four tines were obtained, as shown in Fig.3.



a) ***RT*** b) ***TT***

c) ***CT*** d) ***MT***

Fig. 3 – Woking resistance with working depth curves

Note: The three parts of the curves, i.e. penetration stage, stabilization stage and pull-out stage, were only marked in fig.3 (a), the other graphs had similar characteristics but not be marked

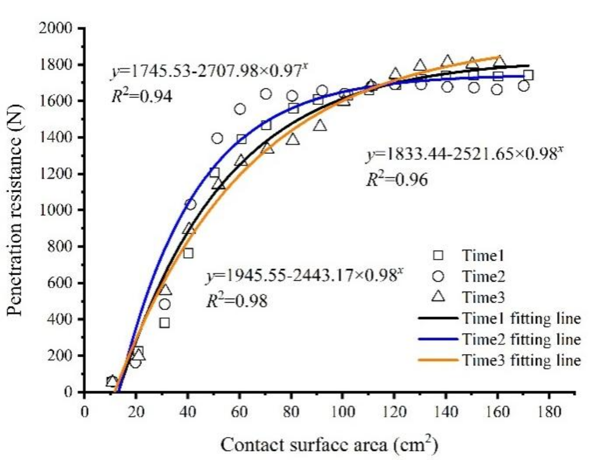
These curves of the very narrow tine mainly consisted of three parts, i.e. penetration stage, stabilization stage and pull-out stage. The graphs showed that all tines got larger resistances in penetration stage than pull-out stage. During the penetration process, the resistances increased with the working depth increasing nonlinearly, and the changing tendencies showed different characteristics between RT, TT, CT, and MT. During the pull-out process, the forces decreased with the working depth decreasing. However, at the early stage of the pull-out process, the force showed increased rapidly at first, then decreased gradually after that. This was caused by adhesive resistance of the contact surface between the tine and the soil. When the adhesive interfaces were broken along the pull-out movements of the tine, the friction force became the dominating resistance of the tine during the pull-out process. In addition, it could be observed that the tines with various geometry obtained different penetration resistance changing tendencies as shown in Fig.3.

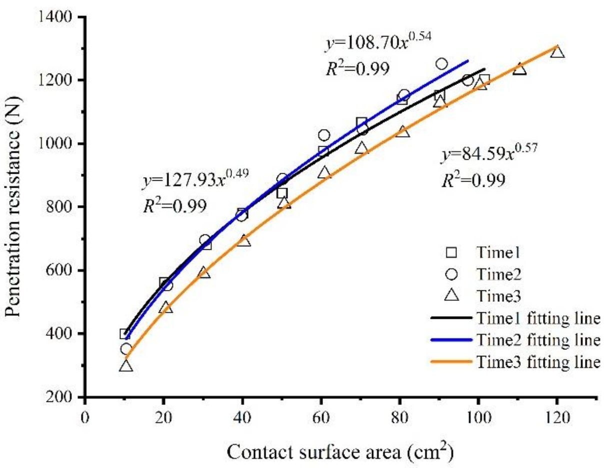
For all tines, CT had the largest penetration resistance and MT got the lowest value when the tine reached the limit depth. Compared to the penetration resistance of RT, the maximum value of TT and MT had average decrease of 28.83% and 36.56% respectively, but an increase of 47.99% for CT. However, it could be seen in Fig.3 that the rectangle tine (RT) obtained different variation curves of the penetration resistance with the working depth from others during its vertical movement. Turning points of the curves were easily observed in Fig.3 (a). The penetration resistance of RT increased sharply at first, then continued to slowly increase with a lower slope. Though CT obtained larger penetration resistance and the penetration resistance curves also showed two parts with different changing rules, the rapid increasing characteristic was not as obvious as the curves of RT were. For TT and MT, the penetration resistances increased stably with no significant phase differences during the entire curves, the resistance values of TT and MT varying much stably than those of RT and CT.

Combined with Fig.3 (a), it could be found that the cutting edges of RT and TT were straight lines while the others were blending lines. The angle between the cutting edge and the penetration direction was defined as the penetration angle. The penetration angles of CT, TT, and MT were all less than 90° (30° for TT, 13°-51° for MT, 90° for RT, and 27°-78° for CT), except the penetration angle of RT which was 90°. Especially, the angles of CT and MT always changed with the working depth during the entire penetration movements but were all less than 90°. These results indicated that the penetration angle affected the resistances a lot, a bigger penetration angle resulted in larger penetration resistance and variation range of the changing tendency, a smaller angle could obtain stable penetration resistance curves during the penetration process. And a tine owing a cutting edge with continuous acute angles was more suitable for operating on natural grassland because of its lower resistance.

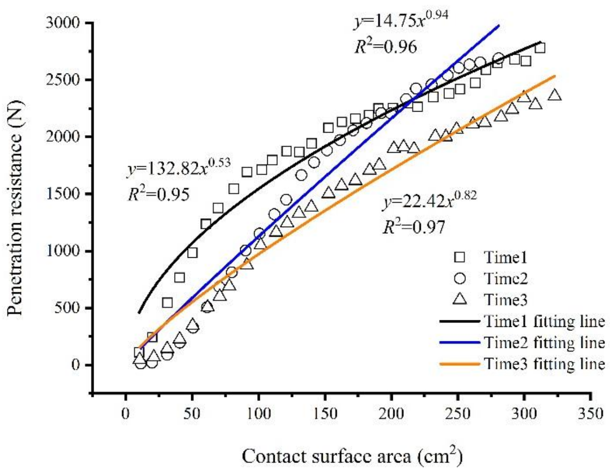
- **Effects of contact surface area on penetration resistance**

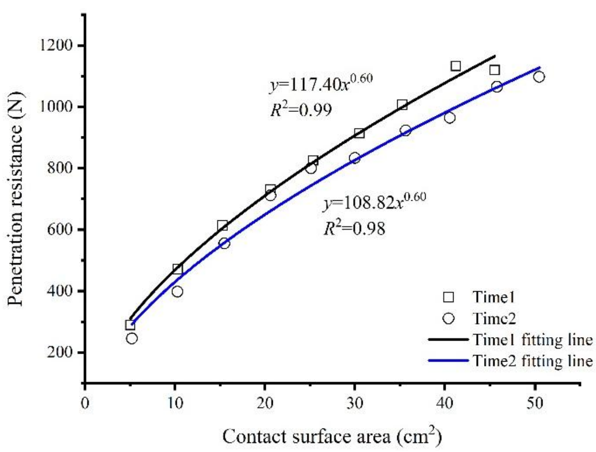
During the tine inserting into the soil on natural grassland, the cutting edge cut off and pressed on the soil layer, resulting in the resistance from the soil, the contact surfaces became the main interaction surfaces between the tine and the soil layer. The interaction forces acted on the contact surfaces and impeded the tines vertical movements, so the contact surfaces also affected the penetration resistance. The contact surfaces of the tine included the cutting edge's surfaces and side surfaces. Via the software of CATIA, 3D models of the tines were drawn, and the contact surface area values under different working depth were measured based on these 3D models. The curves between the contact surface area and penetration resistance were obtained, as shown in Fig.4. The figures showed that all penetration resistances of the tines increased with the contact surface areas increasing nonlinearly with the R^2 value exceeding 0.94. Except for the rectangle tine (RT), the penetration resistances of other three tines owned power function relationships with the contact surface areas with the R^2 value exceeding 0.95. The penetration resistance of RT showed an exponential function relationship with the contact surface area with the R^2 value exceeding 0.94.





a) ***RT*** *b)* ***TT***





c) ***CT*** *d)* ***MT***

Fig. 4 – Penetration resistance with contact surface area curves

In addition, as mentioned before, the penetration angle of the rectangle tine was 90° during all the penetration processes, as shown in Fig.5 (a), however, for the other three tines, the penetration angles (θ) were all less than 90° during the vertical movements (Fig.5 (b)).

A function relationship between the penetration resistance and contact surface area could be concluded as follow:

$$\mathrm{P} = \begin{cases} a + b \cdot c^{x} & (\theta = 90^{\circ}) \\ A + B \cdot x^{C} & (\theta < 90^{\circ}) \end{cases} \tag{1}$$

Where P is penetration resistance (N); θ is penetration angle (°); a, b, c, A, B, and C are constants.

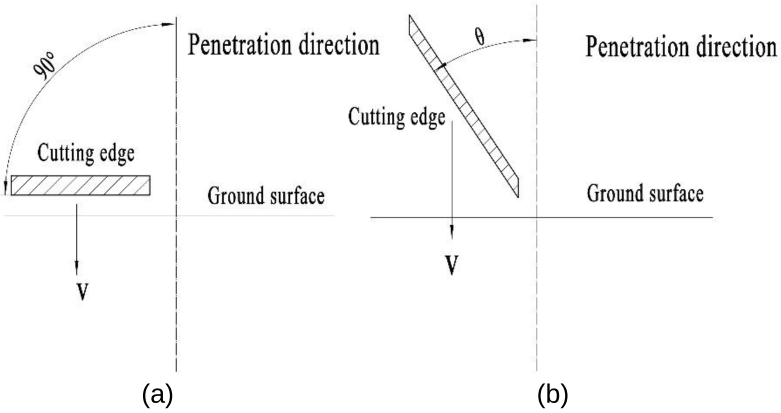


Fig. 5 – Diagram of the penetration angles

- **Surface disturbance on natural grassland after penetration experiments**

When the tine was pulled out from the soil on natural grassland, only a narrow slit was left on the surface. The grass roots and withered grass were cut off, there were no extensive vegetation destruction and overturning soil-roots clods situations found during the penetration experiments, as shown in Fig.6.

Fig. 6 – Surface disturbance during penetration experiments

CONCLUSIONS

(1) The tine geometry affects the penetration resistance substantially. The crescent tine resulted in the highest penetration resistance compared to the rectangle, triangle and mososeries tine, and the mososeries tine got the lowest value during the penetration process. Compared to the rectangle tine, the maximum penetration resistance value of the triangle tine and mososeries tine decreased by 28.83% and 36.56%, respectively, while the value of the crescent tine increased by 47.99%.

(2) The changes of different types, geometries of the tines cause the variation of the contact surface area between the tine and soil which directly affect the penetration resistance during the penetration process. The penetration resistance increases with a power function or an exponential function with the contact surface area with the R^2 values exceeding 0.94. The models could well reflect the variation tendency of the penetration resistance with the contact surface area.

(3) The differences of cutting-edge geometries of the tines resulted in varied curves of the penetration resistance with working depth, which affect the resistance values and changing stability. A bigger penetration angle resulted in larger penetration resistance and variation range of the changing tendency, a smaller angle could obtain stable penetration resistance curves during the penetration process. The tine owing a cutting edge with continuous acute penetration angles was more suitable for operating on natural grassland because of its lower resistance and surface disturbance.

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