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Application of anti-adhesion structure based on earthworm motion characteristics

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ABSTRACT

In the field of agricultural machinery, soil adhesion is a global technical problem that continues to be solved. Reducing soil adhesion is one key issue to improve the operational quality of agricultural machinery. The traditional methods are defective, while the bionics approach can be a reference. Here we extracted and analyzed the surface features of earthworms from the motion perspective, and revealed the laws about how the curvature radii of earthworms changed at three states (stretch, motionlessness, contraction). Based on the characteristics of earthworm motion, we designed the anti-adhesion structure of a press roller. Then the performance of the anti-adhesion structure was experimentally studied, the soil mass adhered was measured. The results showed that the optimal combination of the factors were rubber bulge height = 16 mm (h2) and load = 450 N (F1). To find out why, we compared the surface features at the head and body of earthworm with that of the rubber bulge of the press roller. We found the press roller with the rubber bulge (h2) has the smallest soil mass adhered. Meanwhile, theoretical analysis was carried out to reveal the anti-adhesion mechanism of the rubber bulge structure. Field experiment showed the press roller with rubber bulge structure had a soil mass adhered 37.62% lower than the press roller without such structure. The biomics approach had been such a candidate for reducing the soil adhesion of agricultural machinery.

1. Introduction

Reducing soil adhesion of soil-contacting components of agricultural machines has become a global technical concern. In agricultural or engineering machinery operations, soil adhesion can increase the plowing resistance by more than 30% (Ren et al., 1998), raise the energy consumption of tillage machinery by 30%– 50% (Qaisrani et al., 2010), and decrease productivity by 30% (Tong et al., 2014; Soni and Salokhe, 2006). Therefore, reducing soil adhesion is one key issue to improve the operational quality of agricultural machinery. Over the past century, scholars have probed into the laws of soil adhesion in order to find a better anti-adhesion method. Currently, filling, heating, electro-osmosis, mechanical methods, surface modification, and surface shaping are commonly used to reduce soil adhesion (Khan et al., 2010).

In the filling method, gas or liquid is continuously injected into the contact surface between soil and the working component, forming a gas/liquid interface, which stops the direct contact between the working component and soil, and reduces the contact area and frictional resistance. This method can significantly improve the anti-adhesion ability of the plowing instrument, but should be supplied with lubricants from a special device, which increases energy consumption (Kuczewsi, 1981; Meng et al., 2015).

With the heating method, engine exhaust or another heat source is used to moderately heat the surfaces, which reduces the surface tension of soil water and thereby decreases the adhesive force and soil adhesion. However, this method is effective only in the permafrost zone and causes very high fuel consumption (Li et al., 1996).

As for electro-osmosis, an electric field is produced at the interface between soil and the working component, where direct current is added. Under the electric field, the hydrated cations in soil water migrate to the surface of the working component that is connected to the negative electrode, increasing the interfacial water content and thereby reducing soil adhesion (Formato et al., 2005; Zu and Yan, 2006). However, the use of this method is restricted to high-speed operating agricultural machinery.

There are two types of mechanical methods: additional mechanical devices and vibration methods. An additional mechanical device is actually a cleaning surface device that reduces soil adhesion by scraping or striping the soil adhesion layer on surfaces of the working component (Gupta et al., 1989). The vibration method aims to achieve active

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vibration through the use of additional devices, reducing soil adhesion of the plow or bucket and operating resistance (Li et al., 2012). However, additional mechanical devices or drive devices complicate the whole structure, and are not practical.

With surface modification, the adhesion is reduced by changing the surface properties of solid materials. This method was invented in the 19 th century when Chinese peasants covered agricultural tools with pigskin (Liu, 1962). Many researchers have done similar researches, such as treating mouldboard bar with paraffin or linseed oil (Kummer, 1939), coating agricultural machineries with enamel (Salokhe and Gee-Clough, 1989), covering simple tillage tools with polytetrafluoroethylene (PTFE) materials (Fox and Bockhop, 1965).

The surface shaping method aims to make the interface water film discontinuous or causes stress concentration by reducing the contact area. Examples of surface shaping include ribs on a conventional plow, and bars on a general plow body (Davies, 1924; Ren et al., 1996).

The above six methods and techniques are defective, hard-to-operate, inefficient, complex or bulky. The ideal anti-adhesion mechanism should have the following advantages: simple structure, easy processing, low cost, no additional manipulation and power required, low energy consumption, and high efficiency of about 90% (Ren et al., 1998).

The bionics approach is such a candidate for reducing the soil adhesion of agricultural machinery. Bionics is to study the structures and functions of biological systems, and then to apply them to design and build technical equipment. Inspired by the non-adhesion of soil animals, a bionic anti-adhesion method was proposed, that opened up a new way for the study on reducing soil adhesion (Ren et al., 2004; Ren et al., 2006). A bionic ridge structure can well constrain the flow of soil during compacting process and help soil conserve more moisture (Tong et al., 2015). Soil animals (e.g. *Eiseniafoetida, Fruticicda, Gryllotalpa, Formicidae, Catharsius molossus L.*) have a high anti-adhesion ability after long-term evolution (Shelley, 2004). The surface layer of earthworms has a multi-component mixture that helps to reduce soil adhesion, and three methods (electrical stimulation, transfer and immersion) were used to extract and analyze the body fluid of earthworms (Meng et al., 2014). The property of reducing soil adhesion and resistance of earthworms was reported, and the resistances of head and body decreased by 39% and 29% respectively compared with a steel surface (Liu et al., 2008a). The characteristics of energy saving and soil adhesion reduction for the multi-segment corrugated features of earthworms was found through mechanical analysis (Shi et al., 2005). The above studies are based on the static surface structures of earthworms or other soil animals, but there is no study reporting the effects of earthworm movement on soil adhesion reduction. Here we will study and analyze the effects of earthworms on soil adhesion reduction from the motion perspective, and then extract earthworm surface features, and finally apply them to the press roller.

2. Materials and methods

2.1. Collection and preparation of earthworm samples

Eisenia foetida (Fig. 1), the object of this study, is a common species

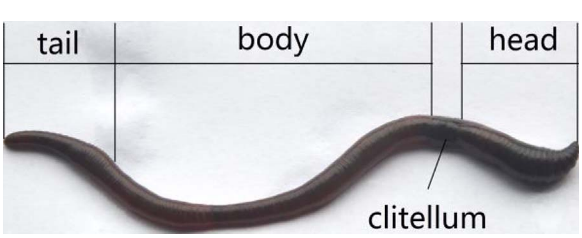

Fig 1. Division of an earthworm sample. The Division includes head, body and tail, and the clitellum is the boundary between the head and body.

of terrestrial earthworms and belongs to Annelida, Oligochaeta, Opisthopora. This earthworm is 60–150 mm long, 3–5 mm wide, 0.4–1.2 g in weight, and has 80–150 segments in the body (Huang et al., 2006).

The earthworms and moist soils collected here were put into a carton and placed in a cool dark area. In each earthworm, all the segments before the clitellum were classified as the head, the last 20 segments were divided as the tail and the middle part was the body. The body and the tail had the same morphological features, so we only studied the head and body of each earthworm.

According to the motion characteristics, three kinds of samples were prepared, including stretch, motionlessness, and contraction (Liu et al., 2008a,b). The samples were prepared as follows:

(1) Stretch samples

For each test, an earthworm was put into the porcelain tray and submerged by 250 ml of water. Then 25 ml of 90% ethanol was slowly added to the tray, so the final concentration was 10%. After 2 h, the earthworm would die and its body was stretched.

(2) Motionlessness samples

For each test, 5 ml of ether was poured into a reagent bottle containing cotton wool before an earthworm was added and the bottle was covered with a lid. After about 10 s, the earthworm would be completely in coma, reaching a relaxed state.

(3) Contraction samples

For each test, an earthworm was placed in 4% paraformaldehyde to sharply contract its body. A few seconds later, the earthworm died in a contracted state.

These three types of specimens were placed on white paper.

2.2. Observation of surface features

The surface features were analyzed with an SZX12 stereomicroscope (OLYMPUS). Each time, after a sample was placed on the stage, we turned on the light source, adjusted the microscope brightness and the angle of the light source, and recorded the image at the desired location. The surface corrugated features are shown in Fig. 2, including the head and the body.

The geometrical parameters of the earthworm surface were measured with an OLYCIATM M3 image analysis system. The collected image was imported into the image analysis system. The geometrical parameters of the earthworm body surface were measured by the length measurement tool and the data was derived. The results are illustrated in Table 1.

Clearly, the width-height ratios are $r_S = 43.90$, $r_M = 8.98$ and $r_D = 4.59$ at the head segment, and $r'_S = 45.42$, $r'_M = 14.25$ and $r'_D = 5.83$ at the body segment (S- Stretch, M- Motionlessness, D- Contraction) (Table 1).

2.3. Surface features extraction algorithm

The images of surface corrugated features were processed in MATLAB R2014a (MathWorks, USA). The surface features were extracted and their fitting curve was obtained. The curve extraction procedure was described in Table A1 in Appendix A.

The above algorithm was used to extract the surface corrugated features of the head and body for the three types of earthworms separately. Finally, 6 groups of experiments were conducted in total, with 5 replications in each group of experiment. The curves were fitted in MATLAB, and then the curvature radius R was solved as follows:

$$K = \frac{|y'|}{(1 + y'^2)^{3/2}} \tag{1}$$

$$R = \frac{1}{K} \tag{2}$$

where K is the curvature; y' and y" are the first and second derivatives of the fitting equation, respectively.