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THE ELECTRO-OSMOTICALLY DRIVEN FLOW NEAR AN EARTHWORM'S BODY SURFACE AND THE INSPIRED BIONIC DESIGN IN ENGINEERING

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ABSTRACT
The electro-osmotically driven flow near an earthworm's body surface is a basic electrokinetic phenomenon that takes place when the earthworm moves in moist soil. The flow in a micro thin layer of water is formed in the vicinity of the earthworm's body surface as a result of the electric double layer interaction. Such a micro scale electro-osmotically driven flow plays the role of lubrication between the earthworm's body surface and the surrounding medium of moist soil and reduces the surface adhesion. The examples of bionic design in engineering inspired by such natural phenomena of the earthworm in soil are reported.
Keywords: anti-adhesion, biomimetics, earthworm, electro-osmotic flow, modelling, nature inspired design.

1 INTRODUCTION

Learning from the nature is an important methodology of engineering and technological design, which has been applied by human beings for thousands of years. Later, these types of design have received support from the development of fluid, solid and structural mechanics. Modern engineering and technological designs have benefited a lot from nature, incorporating the behaviour of animals and the properties of biological objects. Typical examples of this include the design of a self-cleaning surface, a derivation of the lotus leaf effect [1], and the design of a low-drag swimming suit on the basis of the shark-skin effect [2]. The emergence of the word 'biomimetics' is a symbol of modern development of nature inspired designs; it often concerns a combination of different disciplines [3]. Indeed, without the scientific developments in biology, zoology, oceanography, microscopic techniques, mathematics and computer technology, and modern measuring technology, it would be impossible to understand the mechanism of drag reduction in ocean animals and apply it to practical designs.

In this article, a fundamental problem of biomimetics, the electro-osmotically driven flow near an earthworm's body surface, is first analysed and discussed to further understand the mechanism of earthworm on anti-soil adhesion. Later, bionic design in engineering, which is inspired by such natural phenomena of the earthworm in soil, is reported.

2 THE PHENOMENA OF AN EARTHWORM MOVING IN SOIL

There are about 1,800 species of earthworms grouped into five families and distributed all over the world. The most common worms in North America, Europe and Western Asia belong to the family Lumbricidae, which has about 220 species. Earthworms range from a few millimetres long to over 3 feet, but most common species are a few inches in length [4]. An earthworm (Fig. 1) is made up of many small segments known as 'annuli'. These annuli are ridged and covered with minute hairs that grip the soil, allowing the worm to move as it contracts its muscles. At about a third of the worm's length is a smooth band known as the clitellum. The clitellum is responsible for secreting the sticky clear mucus that covers the worm. The earthworm has no gills or lungs. Gases are exchanged between the circulatory system and the environment through its moist skin. Earthworms breathe through their skin, so they must stay moist [5].

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Figure 1: The earthworm.

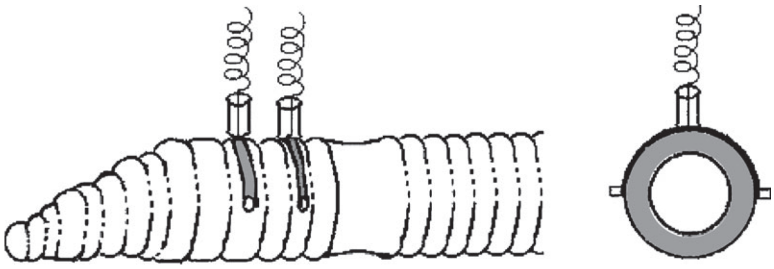

Figure 2: The measurement of the surface electric potential of an earthworm's body tissue.

Earthworms can play a variety of important roles in agro-ecosystems. Their feeding and burrowing activities incorporate organic residues and amendments into the soil, enhancing decomposition, humus formation, nutrient cycling and soil structural development [6]. Earthworm burrows persist as macro-pores, which provide low resistance channels for root growth, water infiltration and gas exchange [7].

An important phenomenon of earthworms moving in moist soil is the electric potential that exists on an earthworm tissue. In general, there are two types of electric potential for all creatures including earthworms, the resting and the action potentials; the surface potential of the living body is a combined reflection of these two types of potential. The resting potential exists between the inside and the outside of the tissue or cell membrane when the body is stationary. When the body is moving, there is an additional action potential between the excited part and the resting part of the same tissue or cells. The action potential is of short duration, but larger than the resting membrane potential. For example, the two types of potential for muscle and nerve cells are 60–90 mV and 90–120 mV, respectively [8]. In an experimental study, Sun *et al.* [9] successfully measured the electric potential distributed on an earthworm tissue (Fig. 2). The resting potential of the earthworm tended to zero with respect to the earth. When it was creeping, the skin of the earthworm had a negative potential at the moving part of the body with respect to the earth and the resting part of the body. The maximum amplitude of surface potential was 40 mV, occurring at its fore part; other details of the measurement are shown in Table 1.

Earthworms could hold the answer to sticky engineering problems. If we move machinery through moist soil, the adhesive forces between the soil and the machinery make the soil stick, causing resistance, increasing energy consumption and reducing the quality of the work. At the same time, however, soil does not seem to adhere to earthworms.

Table 1: Mean and maximum values of an surface electric potential of an earthworm Michaelsen body tissue [9].

	Electric potential of Michaelsen when creeping (mV)		Electric potential of Michaelsen through a tube (mV)	
Position on body	Maximum	Mean	Maximum	Mean
Fore part	40	21	35	20
Middle part	30	11	19	9
Hind part	18	11	18	5

Other possible mechanisms of anti-adhesion, such as the surface secretions of soil animals and the chemical compositions and their surface/body flexibilities, have been summarised by Ren *et al.* in 2001 [10].

3 THE CONCEPT OF THE ELECTRIC DOUBLE LAYER AND ELECTRO-OSMOTIC FLOW

The electric double layer (EDL), which is formed as a result of the interaction of an ionised solution or liquid with static charges on dielectric surfaces, is the reason the electrokinetic phenomena can take place [11]. The first quantitative model of the EDL, which was suggested by Helmholtz in 1879, is a constant capacitance model (CCM). In the framework of this model, the counter ions, which compensate the surface charge, are located at some fixed distance from the surface. Based on Helmholtz's CCM, the second model of the EDL, which is called the diffuse double layer model (DDLM), was developed by Gouy and Chapman in the 1910s. In this model, the counter ions are located near the surface in accordance with Boltzmann's law. Later, a third model of the EDL was proposed by Stern in 1924 and Graham in 1947 [12], in which some part of the counter ions is located at some fixed distance from the surface, forming the Helmholtz layer, and all other counter ions are distributed near the surface in accordance with Boltzmann's law; such a combination of the CCM and the DDLM is known as a triple layer model (TLM).

A typical electrokinetic phenomenon was observed when a glass surface was immersed in water undergoing a chemical reaction, resulting in a net negative surface potential. This influences the distribution of ions in the buffer solution. Ions of opposite charge cluster immediately near the wall, forming the Stern layer, a layer with a typical thickness of one ionic diameter. The ions within the Stern layer are attracted to the wall by very strong electrostatic forces, as recently demonstrated by molecular dynamics studies [13]. Immediately after the Stern layer, the EDL is formed, where the ions' density variation obeys the Boltzmann distribution, which is consistent with the derivation based on statistical mechanical considerations [13].

The electric potential distribution due to the presence of the EDL can be described by the Poisson–Boltzmann equation, which will be presented later. In general, the electrokinetic phenomena can be divided into four categories, namely:

1. Electro-osmosis, which refers to the motion of the ionised liquid relative to a stationary charged surface due to an applied electric field.
2. Electrophoresis, which refers to the motion of a charged surface relative to a stationary liquid due to an applied electric field.
3. Streaming potential, which is the electric field created by the motion of the ionised fluid along stationary charged surfaces (opposite of electro-osmosis).

4. Sedimentation potential, which is the electric field created by the motion of charged particles relative to a stationary liquid (opposite of electrophoresis).

4 ELECTRO-OSMOTICALLY DRIVEN FLOW IN THE VICINITY OF AN EARTHWORM'S BODY SURFACE

4.1 The electrokinetic phenomena

Electrokinetic phenomena can appear when an earthworm moves in moist soil. According to the experimental measurement by Sun *et al.* [9], bioelectricity exists on an earthworm's tissue; an electro-osmotic function can therefore be predicted when the earthworm moves in moist soil where the moist content is composed of water ions. Based on the concept of electro-osmotic flow, when the earthworm is in contact with moist soil, a microscopic electro-osmotic system is formed between its stimulated body parts and the other parts nearby. The molecules or particles of the moist content of soil, i.e. water ions, will migrate from the positive to negative poles under the action of the surface EDL effect. As a result, water ions contained in the adjacent moist soil move to the contact zones by the action of the potential difference. The water film at the contact interface becomes thicker, so that the soil adhesion to the body surfaces would be reduced through lubrication; thus, an electro-osmotically driven flow takes place in the vicinity of the earthworm's body surface and within a micro thin liquid layer.

Although the amplitude of the action potential of the earthworm is small, a microscopic electro-osmotic flow can be formed because the distance between the positive pole and the negative pole is very small. The zone of negative polarity produced by stimulation from the contacting moist soil is on the same surface as the resting body part near the stimulating zone. Figure 3 shows the schematic diagram of the microscopic electro-osmotic system of an earthworm. In practice, the positive pole and the negative pole are normally on the segment near each other and the action potential of an earthworm's body surface appears in the feature of dynamic distribution. Such a system may be called a non-smooth surface electro-osmotic system, as shown in Fig. 4.

4.2 The EDL effect

The EDL interaction should be active when an earthworm moves in moist soil; this will result in an electro-osmotically driven flow in the vicinity of the earthworm's body surface and within a micro thin liquid layer. Taking an isolated earthworm as an example, the electric potential distribution at the earthworm's surface is determined solely by its own fixed charges, which are induced by the stimulation of the surrounding mediums, but dependent upon the interaction with the thin liquid layer

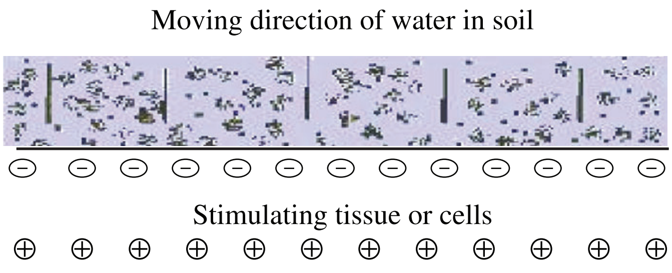

Figure 3: Schematic diagram of the microscopic electro-osmotic system existing on the body surface of an earthworm in moist soil.

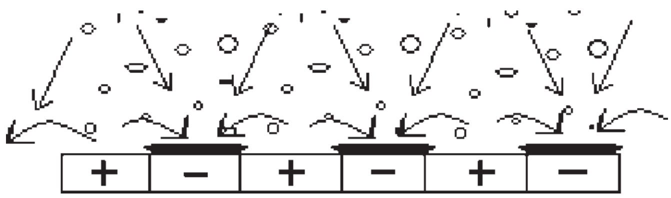

Figure 4: The non-smooth surface electro-osmotic system.

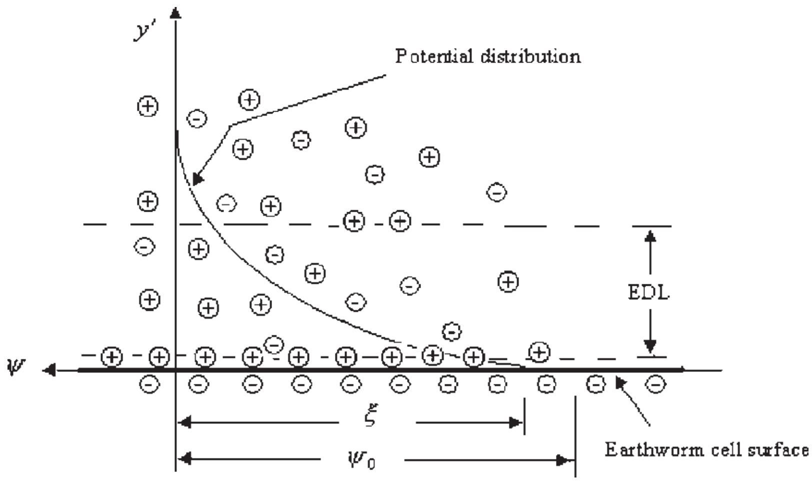

Figure 5: Schematic diagram of the EDL next to a negatively charged earthworm's surface. Here ψ is the electric potential, ψ_0 is the surface electric potential, ξ is the Zeta potential and y' is the distance measured from the surface.

in the vicinity of the surface. Meanwhile, the fixed charges presenting at the surface also contribute to the electric potential distribution at the earthworm's cell surface. Consequently, the electric potential distribution at the earthworm's cell surface changes during the EDL interaction with the micro thin liquid layer. In terms of moving in moist soil, the earthworm's surface is highly dynamic, responding strongly to the environmental changes through adsorption of ions and macromolecules of the moist components of soil.

Figure 5 schematically shows the EDL formed as a result of the interaction of ionised water in moist soil with the negatively charged earthworm's cell surface, where the surface electric potential influences the distribution of water ions in the moist soil. The ions of the opposite charged cluster, i.e. the water ions in the moist soil, immediately move towards the earthworm's surface to form the Stern layer, which has a typical thickness of one ionic diameter. The ions within the Stern layer are attracted to the earthworm's surface, where the negatively charged electric forces are strong. Immediately after the Stern layer, the EDL is formed, where the variation of ions' density obeys the Boltzmann distribution.

The electric potential distribution due to the presence of the EDL is described by the Poisson–Boltzmann equation:

$$\frac{\mathrm{d}^2\psi^*}{\mathrm{d}y'^2} = \frac{-4\,\pi\,h^2\rho_\mathrm{e}}{D\,\xi} = \beta\sinh(\alpha\,\psi^*), \tag{1}$$

where ψ^* $(= \psi/\xi)$ is the electro-osmotic potential normalised with the Zeta potential ξ, y' is the distance measured from the surface, ρ_e is the net electric charge density, D is the dielectric constant and α is the ionic energy parameter given as

$$\alpha = e\,z\,\xi/\kappa_B\,T, \tag{2}$$

where e is the electron charge, z is the valence, κ_B is the Boltzmann constant and T is the temperature. The variable β relates the ionic energy parameter α and the characteristic length h to the Debye–Hückel parameter ω as

$$\beta = \frac{(\omega\,h)^2}{\alpha}, \quad \text{where } \omega = \frac{1}{\lambda_D} = \sqrt{\frac{8\pi\, n_0 e^2 z^2}{D\,\kappa_B T}}. \tag{3}$$

The Debye length λ_D is a function of the ion density n_0, as given by eqn (3). For aqueous moisture content of soil, say water, at 25°C, the ion densities of 1 mol/m^3 and 100 mol/m^3 approximately correspond to the Debye lengths of $\lambda_D = 10$ nm and $\lambda_D = 1$ nm, respectively [10].

When considering the earthworm problem as two-dimensional axisymmetrical and assuming the Zeta potential to be known and to remain constant along the earthworm's surface, eqn (1) can be simplified as

$$\frac{d^2\psi^*}{d\eta^2} = \beta\ \sinh(\alpha\psi^*), \tag{4}$$

where $\eta = y/h$ and h is the average thickness of the thin liquid layer near the earthworm's surface. Multiplying both sides of this equation by $2(d\psi^*/d\eta)$ and integrating with respect to η, the following relation is obtained:

$$\frac{d\psi^*(\eta)}{d\eta} = \sqrt{2\,\frac{\beta}{\alpha}\left[\cosh(\alpha\psi^*) - \sinh(\alpha\psi_c^*)\right]}, \tag{5}$$

where both the electric potential and its spatial gradient at point η are represented as a function of the electric potential. The relation of y and h is illustrated in Fig. 6.

For $\alpha \geq 1$ and $\lambda_D \ll h$, the electric potential outside the boundary of the micro thin liquid layer (i.e. $y = 0$) is practically zero. Hence, for $\eta = 0$, $\psi_c^* \to 0$ and after being integrated once more, the term in eqn (5) can be further simplified as [11]

$$\psi^*(\eta^*) = \frac{4}{\alpha}\tanh^{-1}\left[\tanh\left(\frac{\alpha}{4}\right)\exp(-\sqrt{\alpha\,\beta}\,\eta^*)\right], \tag{6}$$

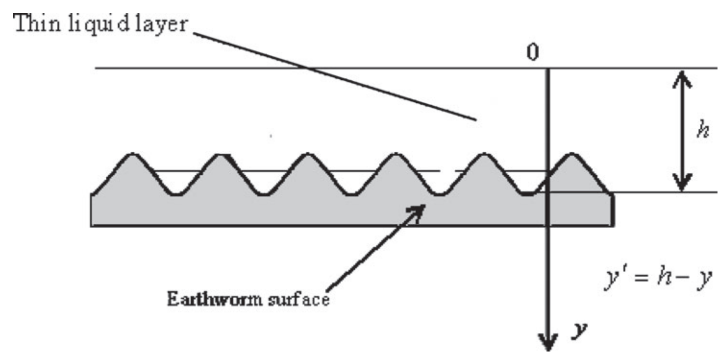

Figure 6: An illustration of the coordinates.

where $\eta^* = 1 - |\eta|$ is the distance from the earthworm's surface. Obviously, a numerical solution can be obtained for different α and β values. In fact, from eqn (3), $\sqrt{\alpha\,\beta}\,\eta^*$ can be regarded as a near wall parameter χ, and

$$\sqrt{\alpha\,\beta}\,\eta^* = \omega\,h\,\eta^* = \omega\,h(1-\eta) = \omega\,h\,(h/h - y/h) = \omega\,(h-y) = \omega\,y' = \chi, \tag{7}$$

so that eqn (6) can be represented as a function of the near wall parameter as

$$\psi^* = \frac{4}{\alpha}\tanh^{-1}\left[\tanh\left(\frac{\alpha}{4}\right)\exp\left(-\chi\right)\right]. \tag{8}$$

Thus, an analytical solution is obtained and represented in Fig. 7.

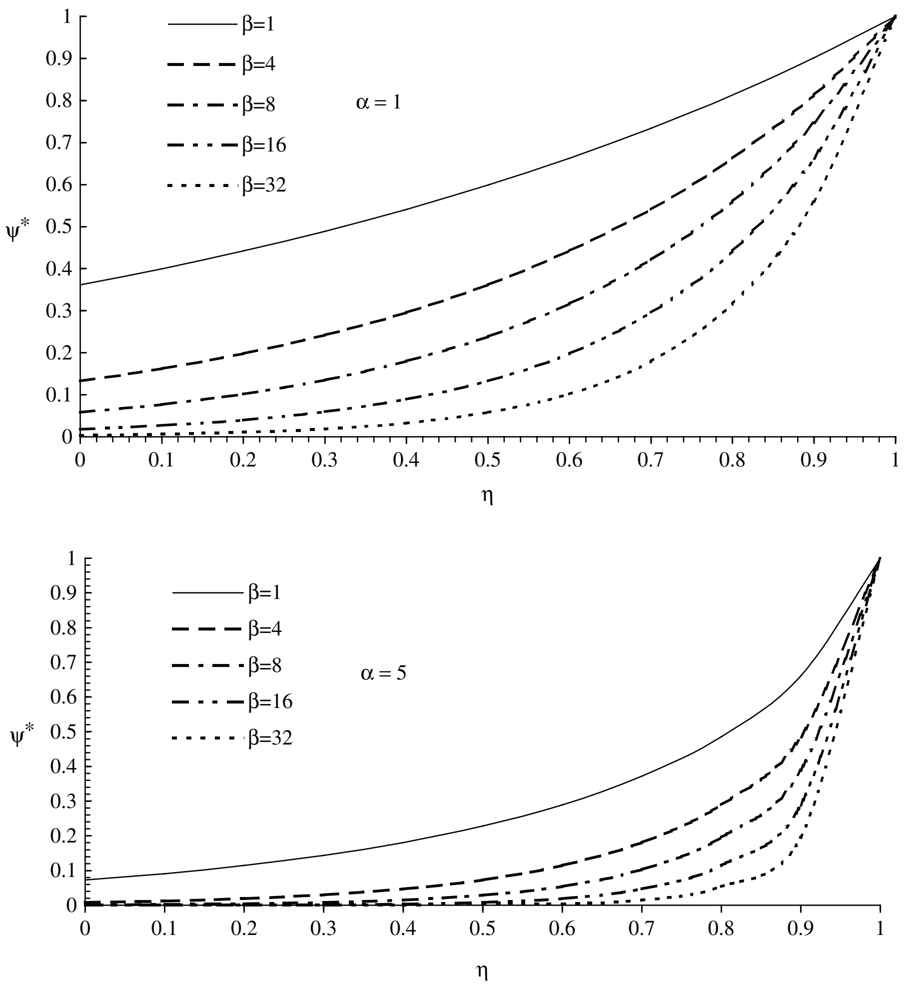

Figure 7: Variation of the normalised electro-osmotic potential ψ^* away from the earthworm's surface for different values of α and β.

4.3 The transport equations

Electro-osmotic flows are normally generated when an external electric field ($\vec{E}$) is applied in the presence of the EDL. In terms of an earthworm moving in moist soil, the electric field is generated by the surface electric potential. The electric field interacts with the EDL and creates the electrokinetic body force in the micro thin liquid layer in the vicinity of the earthworm's surface.

The motion of the ionised incompressible fluid (assuming pure water migrates from the moist soil to the earthworm's body surface by the EDL effect) with electro-osmotic body forces should be governed by incompressible Navier–Stokes equations:

$$\rho_f \left(\frac{\partial \vec{u}}{\partial t} + \left(\vec{u} \cdot \nabla \right) \vec{u} \right) = \nabla p + \mu \nabla^2 \vec{u} + \rho_e \vec{E}, \tag{9}$$

where p is the pressure, $\vec{u} = (u, v)$ is a divergence-free velocity field ($\nabla \vec{u} = 0$) subject to the non-slip boundary conditions at soil animal surfaces, μ is the fluid viscosity, ρ_f is the liquid density and ρ_e is the net charge density determined by the Poisson–Boltzmann equation as given in eqn (1). The electric field is represented by $\vec{E} = -\nabla \psi$, where the electric potential (ψ) is obtained from

$$\nabla \cdot (\sigma \ \nabla \psi) = 0, \quad \text{where } \sigma \text{ is the electric conductivity.} \tag{10}$$

To solve the above transport equations, the following conditions may be assumed: (1) the thin layer fluid is a Newtonian fluid (pure water); (2) the fluid viscosity is independent of the local electric field; (3) the Poisson–Boltzmann equation (1) is valid, so that the effects of ions' convection may be negligible; (4) the fluid permittivity does not change with $\vec{E}$; (5) the Zeta potential is uniform. Based on these, numerical solutions can be obtained by solving the coupling problem of electro-osmotic flow, described by eqn (4), and the potential distribution in the presence of the EDL described by eqn (1). A numerical procedure based on the finite volume method for solving the coupling problem of fluid flow and heat transfer with external electric body forces has been developed in the first author's recent work [14], which can be further improved to solve the current problem.

The interface velocity condition is important in order to assess the interaction of the flow within the EDL. The Helmholtz–Smoluchowski electro-osmotic velocity u_p was derived from an analysis in the absence of pressure gradients in balance between the viscous diffusion terms and the electro-osmotic forces:

$$u_p = -\frac{\xi \, \varepsilon \, E_x}{\mu}, \tag{11}$$

where ε is the fluid permittivity. It is noted that the EDL has an effective thickness of the order of 1–100 nm, but the micro roughness or non-smoothness of a soil animal's surface is normally of the order of 5–100 μm, as shown in Fig. 8 [10], and accordingly the micro thin liquid layer in the vicinity of the surface may be assumed to be of the order of approximately 50–150 μm. This presents a great challenge to the numerical simulation of such electro-osmotically driven flow; therefore, one should develop a unified slip condition, which incorporates the EDL effects by specifying an appropriate velocity slip condition at the interface between the surface of the earthworm and the thin liquid layer induced by the electrokinetic effect. The microscopic observation of an earthworm creeping in moist soil can show that the ionised water velocity in the micro thin liquid layer extended up to the earthworm's body surface has an almost constant slip value equivalent to u_p, the Helmholtz–Smoluchowski velocity.

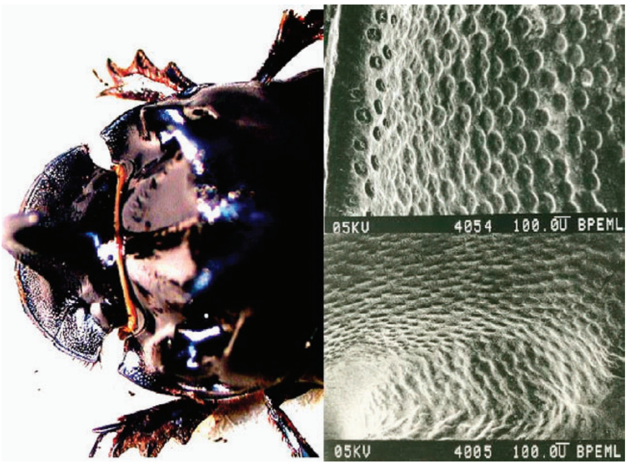

Figure 8: Soil animal – dung beetle.

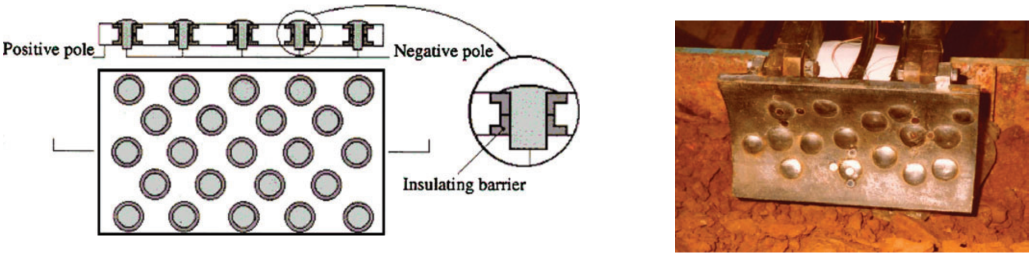

Figure 9: The electro-osmotic system designed for a bulldozing blade.

5 APPLICATIONS IN ENGINEERING DESIGN

Obviously, to fully understand the mechanism of anti-adhesion of such soil animals as earthworms, much theoretical and experimental study is yet to be done. Nevertheless, initial design and applications to engineering have already been made. At the Bionics Engineering Laboratory, Jilin University, Changchun, the surface electro-osmosis systems, as shown in Fig. 9, have been designed and applied to engineering equipment. Figure 9 shows the electro-osmotic system designed for a bulldozing blade, which has been tested at the laboratory. It was found that, under the same conditions, soil stuck on the surface of a conventional plate or a prepared non-smooth surface without electro-osmosis, but almost no soil stuck on the designed bionic non-smooth electro-osmosis plate. Compared with the corresponding non-smooth surfaces without electro-osmosis, the designed biomimetic with electro-osmosis can reduce bulldozing resistance by approximately 9–12% for the embossed non-smooth surface and approximately 15–32% for the corrugated non-smooth surface, respectively, under only 12 V.

The electro-osmosis and bionic non-smooth methods described above have been applied to other engineering projects in order to reduce adhesion and improve the working efficiency of machinery. These include the non-smooth electro-osmosis coal hopper in steam thermal power plants, the lining steel chains installed in dump trucks, the flexible steel lining in the scraper bucket of a loader and the bionic non-smooth plough mouldboard in the agricultural industry [15].

All of the current applications developed by the authors, as stated above, are amied at reducing the adhesion of soil to the working machinery tools. Indeed, the adhesion forces of soil, which exist when soil is in contact with a solid interface, often poses problems for soil engaging components of vehicles and machines, such as earthmovers, excavator buckets and bulldozers, and result in decreased output. However, it is very clear that the phenomena of soil adhesion disappear when soil-burrowing animals move in soil. In addition, recent research has found more evidence that such soil animals' excellent ability of anti-adhesion, apart from the electro-osmosis effect, partly results from their non-smooth surface morphologies [10, 15]. One such example is the body surface of a dung beetle, whose non-smoothness or roughness of the order of micro scales, as shown in Fig. 8. In addition, the theory of non-smooth morphology has also played a very important role in anti-wear of machinery tools [16, 17].

6 CONCLUSIONS

In this paper, the electro-osmotically driven flow, which takes place when an earthworm moves in moist soil and its role in anti-adhesion are analysed. The mechanism of EDL interaction on the earthworm's cell surface, the process of forming the micro thin liquid layer in the vicinity of the surface and the electro-osmotically driven flow are discussed. The authors attempted to show how the EDL theory and the concept of electro-osmotic flow are the fundamental backbone for anti-adhesion or drag reduction problems. It is encouraging that such a relatively simple concept can provide practical estimates of the interactions between biological surfaces and their surrounding mediums with ionised liquid such as pure water; this will be essential for biomimetic design of mechanically prepared surfaces in similar mediums. After presenting and discussing the Poisson–Boltzmann equation for the EDL effect, an analytical solution for the normalised electric potential near the earthworm's cell surface is obtained. Furthermore, the transport equations for electro-osmotic flow and the corresponding numerical strategy are generally discussed. The surface electro-osmosis systems designed for soil machinery tools are presented as examples of nature inspired bionic design and practical applications are reported.

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