Study of soil-solid adhesion by grey system theory *

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Abstract The adhesion of soil to solid surface is a complicated interfacial reaction that relates to many factors. Quantitative descriptions of the forming procedures and the conditions of the adhesion interface forming can provide a guidance to the design of the soil-engaging component surfaces with a good anti-adhesion performance. Using a self-developed soil adhesion measurement device, the mean area and mean thickness of the adhesion interface waterfilm and the interfacial adhesion force varied with soil water content and vertical loads are measured. According to the gray system theory, the differential equations of the mean area and the mean thickness of waterfilm and the adhesion force of the interface are developed. The consequences between or among the factors related to the adhesion interface forming process are analyzed quantitatively with the gray correlation analyzing theory. The forming procedure of the adhesion interface and the influence on the mechanic behaviour of soil adhering on a solid surface are demonstrated by the experiments. The analysis will be beneficial to designing of soil-engaging component surfaces of terrain-machines.

Keywords: **soil, adhesion, grey system analysis, interfacial reaction, waterfilm.**

In agricultural machinery systems, soil adhesion to the non-soil material surfaces is a common phenomenon[1~3]. In most cases, it is harmful to normal soil manipulation, because it causes decrease of productivity, increase of energy consumption, and degrading of the quality of soil manipulation[4,5]. The study on soil adhesion has lasted for 80 years, and most researches focus on soil adhesion mechanisms, the techniques of reducing soil adhesion and resistance, and so on.

There are several theories that explain soil adhesion mechanisms in different ways, including water tension theory[6], capillary attraction theory[3], the theory about comprehensive reaction of capillary attraction and the waterfilm viscous force[7~9], chemisorption theory1), and so on. Nevertheless, all these theories or models are qualitative. Indeed, efforts have been made in order to quantitatively analyze the relationships among soil adhesion, friction, soil moisture content, normal load exerted on soil, and the physical or chemical characteristics of solid material surface[7]. However, these efforts are based on traditional numerical regression analysis. That is, to fit a group of data with a suppositive equation. It is inaccurate when there are not enough experimental data available. Therefore, the current quantitative methods used for analyzing soil adhesion are comparatively rough. With these methods, the essential factors that affect soil adhesion cannot be quantitatively taken into account, hence, the soil adhesion phenomena under specific conditions cannot be quantitatively predicted and interpreted. Besides, the above theories or methods lay emphasis particularly on microcosmic analyzing, revealing little about the causality between microcosmic behaviors and macroscopic mechanical behaviors. In summary, the current methods used for analyzing soil adhesion are far from enough to provide a guidance in applications.

As to the soil adhesion reducing methods and techniques[5], which is limited by the guidance of the quantitative theory, the design methodologies mainly rely on experimental methods, and the results obtained are hard to be optimized. Especially, when the working condition of the designed component varies, the adjustment to design cannot be quantitatively made and optimized through computer simulating. The only way to make adjustment is to perform physical model experiments, which costs a lot and is time-consuming.

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1) Cong, Q. Studies on the mechanism of adhesion and resistance reduction by non-smooth surface and studies on bionic shape changing of soil-touching parts. Ph. D. Dissertation, Jilin University of Technology, 1992.

To sum up, deepening study on soil adhesion relies on a quantitative study on soil adhesion mechanisms. By measuring the states of interfacial waterfilm between soil and solid surface under the action of interfacial normal loads, and also by the initiative exploiting of grey system theory[10] in soil adhesion research area, this study carries out relevance analysis among changes of normal loads on the adhesion interface, changes of states of interfacial waterfilm, and changes of interfacial adhesion. This study supplements in quantitative way the current soil adhesion theories about the role of interfacial waterfilm in soil adhesion phenomena. It makes reasonable explanations for the forming procedure, forming conditions of soil adhesion interface, as well as the influence of interface changes on adhesion behaviors. The analysis provides a basis for the optimized surface design of soil-engaging components of terrain-machines.

1 The structure of soil adhesion interface system

The adhesion of soil to solid surface is an interfacial reaction, which is affected by a number of factors. There are many complicated interactions among these factors. In general, the soil adhesion to solid surface is mainly influenced by three classes of factors — soil, solid material and outer impacts[3]. Soil itself is a material that is granular, scattered and porous. Soil is also a discrete and scattered system that is composed of materials in three states — soil (mineral, organism, etc.), liquid (soil water) and gas (the air fulfilled in soil). The dynamic characteristics of soil are determined by the volume, shape, nature, interactions and the proportion of each element in soil. The nature of solid materials and the geometrical morphologies of solid surfaces also have great influences[1,2]. Besides, the other environmental impacts, such as normal load on soil, is regarded as the greatest factor that causes the macroscopic soil-solid force[3]. According to what has been noted above, soil adhesion system can be described by a multi-input single-output system illustrated in Fig. 1, in which $G(s)$ stands for the transfer function between multiple input variables and the output (interfacial adhesion force) of the soil adhesion system.

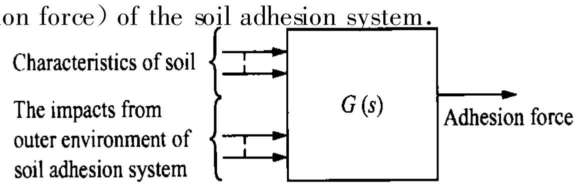

Fig. 1. A model of soil adhesion system.

Up to now, it is known that the shape or distribution of interfacial waterfilm (mainly composed of loose constrained water) is one of the most important factors that directly contributes to the generation and development of interfacial adhesion force. Consequently, all the factors, including the characteristics of soil and the solid material, the geometrical morphologies of solid surfaces and outer impacts of adhesion interface, affect the soil adhesion force by affecting the states of interfacial waterfilm. Thus, soil adhesion system can be further described as that in Fig. 2.

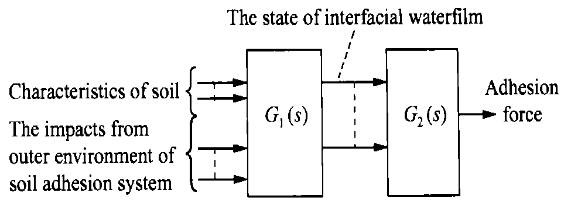

Fig. 2. A model of soil adhesion interface system.

The states of waterfilm refer to the shape and distribution of waterfilm. In this work, the states of waterfilm are approximately expressed by mean area and mean thickness of waterfilm. For homogeneous soil, and under uniform experimental conditions, this approximation is reasonable. Therefore, Fig. 2 can also be simplified to that in Fig. 3, in which W, P, N, S, and d represent respectively soil water content, interfacial adhesion force, normal load exerted on interface, mean area of interfacial waterfilm and mean thickness of interfacial waterfilm.

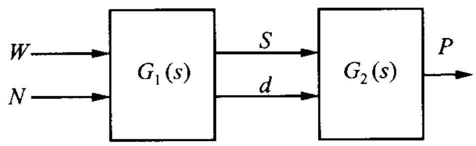

Fig. 3. A simplified model of soil adhesion system.

The soil adhesion system belongs to the grey system in nature. First, the factors related to soil adhesion are numerous, and, the relationships between or among these factors are partly known or completely unknown. Second, being limited by devices or the manner itself of soil experiment, the data obtained from soil experiments are generally limited, and its repeatability and credibility are not high.

Grey system theory is suitable for processing soil adhesion system. To make analysis with grey system theory, neither a large sample of data nor the distribution law of the data sample is necessary. Besides, the theory has less computation. Moreover, it can also eliminate the influences of casual factors on sample of data. Furthermore, by setting up a grey differential equation of a variable with limited discrete experimental data, the continuous track of the variable can be obtained. Grey correlation analysis can determine whether there exists causality or correlation between two factors, as well as the magnitude of such a relation. In conclusion, grey system theory is a proper tool for quantitative analysis of soil adhesion system.

2 Analysis of forming procedure of soil adhesion interfaces by grey system theory

2.1 Design of the soil adhesion experiment

A self-developed device for measuring the states of soil adhesion interface is shown in Fig. 4[1)]. While exerting a 0 ~ 150 N normal load on the negative pole plate, area and thickness of the interfacial waterfilm between the negative pole plate (smooth metallic conductor) and soil are measured. Here, the area of the negative pole plate is 3217 mm^2, the area of the positive pole plate is 23400 mm^2, and the height of the soil sample is 100 mm.

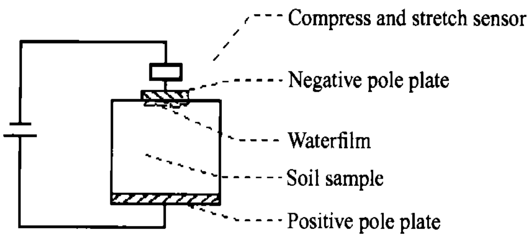

Fig. 4. Mechanism of soil adhesion measurement apparatus.

Soil used in experiments is clay loess, whose mechanical components are shown in Table 1. Soil samples with different water content are obtained through the process of air-drying, grinding, filtration, weighting, and adding water. After soil samples had been sealed for one week, the water contents of soil samples became uniformly distributed.

Table 1. Mechanical components of clay loess

Liquid limit (%)	Plasticity limit (%)	Granule content (%) 0.1 ~ 0.05 mm	0.05 ~ 0.01 mm	0.01 ~ 0.005 mm	0.005 ~ 0.001 mm	< 0.001 mm
33.02	14.49	32.5	36.0	9.5	13.0	90

Selecting a soil sample from the prepared samples with different water contents, measurements are taken under different normal loads. In order to eliminate errors caused by manipulation and the measurement method itself, the measurement is repeated three times for each measurement point. At each experiment point, the load exerted on soil has been kept for 40 seconds. To repeat the same manipulations for five times with two soil samples with different water content (between plastic limit and liquid limit), two groups of data are obtained and listed in Table 2.

Table 2. Raw data of soil adhesion experiments

W(%)	P(kPa)	N(N)	S(mm^2)	d(μm)
20	0.01	13.72	2286.29	0.779
20	0.14	23.52	2533.70	0.902
20	0.21	33.32	2555.42	0.906
20	0.25	43.12	2657.28	0.910
20	0.67	101.92	3120.90	1.316
27.5	0.45	8.82	2647.7	0.83
27.5	0.96	18.62	3068.5	0.93
27.5	1.43	28.42	3139.4	1.04
27.5	1.88	43.12	3152.0	1.26
27.5	2.92	101.92	3168.0	2.40

2.2 Analysis of soil experiment with grey system theory

Let x_0, x_1, x_2, x_3 represent respectively soil adhesion force P, normal load N, the mean waterfilm area S, and the mean waterfilm thickness d.

According to grey system theory, a raw data sequence needs to be converted into an AGO data sequence by accumulated generating operations (AGO). All variables in grey differential equations are AGO variables. Generally, the data in an AGO sequence ascend in exponential law. Therefore, assume the formats of $S-N$ equation, $d-N$ equation, and $P-N$ equation are as follows:

$$\frac{dx_2^{(1)}}{dt} + a_s x_2^{(1)} = u_s, \quad (1)$$

$$\frac{dx_3^{(1)}}{dt} + a_d x_3^{(1)} = u_d, \quad (2)$$

$$\frac{dx_0^{(1)}}{dt} + a_p x_0^{(1)} = u_p, \quad (3)$$

where a_s, u_s, a_d, u_d, a_p, u_p are parameters to be identified. By using the least square method, the parameters of Eqs. (1) ~ (3) are identified and listed in Table 3. The three equations describe how adhesion force P, the area of waterfilm S, and the thickness of waterfilm d vary under different normal loads. As is known, the raw data are only the measurement of those limited and discrete experiment points. However, once the above equations have been set up, it is

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easy to get the rule of how P, S, and d continuously vary when normal load N increases continuously.

Table 3. The identified parameter values of Eqs. (1), (2), (3)

W (%)	a_s	u_s	a_d	u_d	a_P	u_P
20.0	−0.0708	2186.6	−0.1337	0.6556	−0.6148	0.0462
27.5	−0.0099	3044.1	−0.3745	0.2592	−0.3667	0.6043

The correlation relationships of $N-S-d$ and $P-N-S-d$ are analyzed by using grey correlation analysis. When water content is 20.0% or 27.5%, the correlation coefficients are listed respectively in Table 4 and Table 5, where, ε_{01}, ε_{02}, ε_{03}, ε_{12} and ε_{13} stand respectively for the correlation coefficient of $x_0(P)$ and $x_1(N)$, coefficient of $x_0(P)$ and $x_2(S)$, coefficient of $x_0(P)$ and $x_3(d)$, coefficient of $x_1(N)$ and $x_2(S)$, coefficient of $x_1(N)$ and $x_3(d)$. The data in Table 5 are plotted in Fig. 5.

Table 4. Correlation coefficients of N, S, d

N	ε_{12} (W=20%)	ε_{13} (W=20%)	ε_{12} (W=27.5%)	ε_{13} (W=27.5%)
8.82			0.7857	0.8073
13.72	0.7998	0.8119	0.7109	0.7800
18.62	0.8885	0.8605	0.6632	0.7571
23.52	0.6946	0.7184	0.6373	0.7348
28.42	0.6684	0.6923	0.6145	0.7098
33.32	0.6511	0.6757	0.6396	0.7276
43.12	0.5672	0.5639	0.6284	0.6531
53.00	0.6624	0.6625	0.7539	0.7585
63.00	0.8563	0.8478	1.0000	0.9509
73.00	0.9758	1.0000	0.7778	0.8580
83.00	0.6647	0.6825	0.5747	0.6484
93.00	0.4871	0.5005	0.4427	0.5070
101.92	0.3741	0.3841	0.3518	0.4050

Table 5. Correlation coefficients of P, N, S, d

N	ε_{01}(W=20%)	ε_{02}(W=20%)	ε_{03}(W=20%)	ε_{01}(W=27.5%)	ε_{02}(W=27.5%)	ε_{03}(W=27.5%)
8.82				0.8977	0.7885	0.8197
13.72	0.9269	0.5818	0.5934	0.8278	0.7333	0.8424
18.62	0.9086	0.5192	0.5376	0.7682	0.7077	0.8707
23.52	0.9041	0.4835	0.5045	0.7124	0.7154	0.9065
28.42	0.9372	0.4722	0.4938	0.6558	0.7357	0.9524
33.32	1.0000	0.4873	0.5123	0.6594	0.7830	0.9905
43.12	0.4495	0.8219	0.8096	0.5455	1.0000	0.9929
53.00	0.5110	0.9941	0.9942	0.6413	0.9775	0.9667
63.00	0.6205	0.8100	0.8240	0.8260	0.8799	0.9403
73.00	0.8421	0.6326	0.6510	0.8802	0.7910	0.9139
83.00	0.7978	0.5044	0.5231	0.6109	0.7109	0.8876
93.00	0.5508	0.4087	0.4260	0.4521	0.6387	0.8616
101.92	0.3994	0.3429	0.3581	0.3469	0.5808	0.8384

According to Grey system theory, the correlation coefficient of two factors reflects the similarity and correlative extent of the developing trends of two factors. The bigger the correlation coefficient of two factors is, the more similar the developing trends of two factors are, and the more obvious the cause-effect relationship between two factors is.

Intuitively, the raw data in Table 2 can roughly reflect the developing trends of the variables of soil adhesion system. The adhesion force, the area of waterfilm and the thickness of waterfilm are increased with the increase of normal load on soil, when water content is fixed. After the normal load exceeds a certain value, the increase of adhesion force, the area of waterfilm and the thickness of waterfilm begin to be slowed down. For example, the area of waterfilm increases slowly towards the area of the measuring plate. The phenomenon is more obvious when soil water content is higher.

On the other hand, the correlation coefficient curves in Fig. 5 also provide a lot of information as follows:

(1) The developing process of soil adhesion force has experienced three stages. At the first stage, the function of normal load is mainly to compress soil pores. With the rise of normal load, ε_{01} falls from the local maximum to the local minimum, so do e_{12} and e_{13}. This means that the developing velocities of area and thickness of waterfilm are very slow with the normal load increasing, and it is quite possible that the developing procedures of the area and thickness of waterfilm have dead zones if soil water content is low. In addition, at this stage, the rising speed of interfacial adhesion force is much lower than that of the normal load. The normal load is mainly used to compress soil pores, and contributes little to the forming of waterfilm nearby the soil-solid interface. The less the soil water content is, the faster the drop of velocity of e_{01} is, and the slower is the increase of the velocity of interfacial adhesion. At this stage, interfacial adhesion is mainly influenced by hygroscopic water

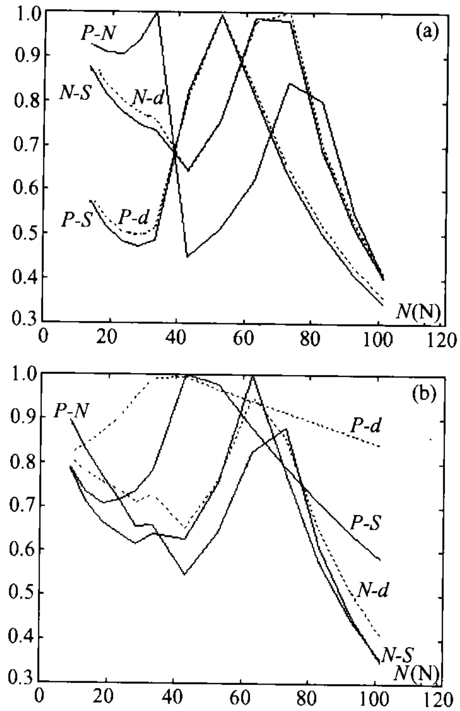

Fig. 5. Correlation coefficient curves between various factors. Water content: (a) 20.0%, (b) 27.5%.

and membranous water in soil nearby soil-solid interface.

At the second stage, with the increase of normal load, e_{01} rises from the local minimum to the local maximum, so do e_{12} and e_{13}. This trend shows that area and thickness of waterfilm increase rapidly while the normal load increases, because normal load has greatly compressed soil pores, and made them being fulfilled with soil water. When the normal load is continuously increasing the water in soil pores is pressed to the soil-solid interface. Therefore, the area and thickness of waterfilm nearby the interface increase rapidly. Meanwhile, the adhesion force increases rapidly. At this stage, the capillaceous water filled in soil pores plays a primary role in the forming and developing of interface waterfilm.

At the third stage, with the gradually increasing of normal load, e_{01} curve goes down again from the local maximum toward zero, so do e_{12} and e_{13}. At this stage, with the increase of normal load, the area and thickness of waterfilm reach to their limits. Their increasing speeds slow down, so does the increasing speed of soil adhesion. Soil has already been tamped. It needs more normal load to compress soil water filled in soil gap to the adhesion interface. If water content in soil is high, it is very possible that the soil water is saturated and becomes gravity water.

(2) Curves of e_{12}, e_{13} and e_{01} are similar in shape. According to the definition of grey correlation coefficient, it means that the cause-effect correlation intensities of N-S and N-d are similar to that of P-N. In physical meaning, the area and thickness of soil waterfilm are the intrinsic powers that drive soil adhesion system. In other words, the normal load affects interfacial adhesion by affecting the state of waterfilm nearby the interface. Besides, at the second developing stage, e_{01} curve lags behind e_{12} and e_{13} curves along the normal load axis. The less the soil water content is, the bigger the lags are. This further proves that normal load affects interfacial adhesion by affecting the states of waterfilm nearby the interface. Moreover, the difference between e_{01} curve and e_{12} and e_{13} curves along the normal load axis can be taken as a measurement for soil properties, such as water content, sticky particle content, the size of soil pores, and so on.

(3) At most points along the normal load axis, e_{12} is smaller than e_{13}. The higher the soil water content, the greater the difference. This geometrical feature suggests that the increasing speed of interface thickness is higher than that of interface area. If the soil water content is very high, it is easy for interfacial area to approach to its limit. In this circumstance, the increase of interface thickness contributes the most to the increase of interfacial adhesion. This can also be confirmed by the fact that, in Fig. 5, when soil water content is higher, the distance from e_{03} curve to e_{02} curve is bigger.

The above analysis shows that the waterfilm does play a critical role in soil adhesion systems. Therefore, the description in this paper of the mechanism of soil adhesion system is reasonable.

Refs. [12, 13] analyzed the soil adhesion reducing function of soil-burrowing animal body surfaces. Ref. [14] designed several bionic bulldozing plates by imitating the geometric characteristics of soil animal body surfaces. Experiments verified that, compared with traditional bulldozing plates with smooth surfaces, the bionic bulldozing plates could reduce soil adhesion more effectively.

According to what has been analyzed in this paper, it could be deduced that, on surfaces of soil-engaging components of terra-machines, proper numbers, sizes, and distributions of protuberances will do good to soil adhesion reducing. Following are the explanations:

(1) SEM analysis shows[7] that soil adhesion interface has several contacting states with the varying soil water content and outer conditions. (i) Micro-soil protuberances do not contact solid surface; (ii) point contact of liquid and micro-protuberances of soil; (iii) ring contact of liquid and micro-protuberances of soil; (iv) ring contact of liquid and soil particles; (v) mass contact of waterfilm and micro-aggregates of soil; (vi) mass contact of waterfilm and soil clod. If proper numbers, sizes, and distributions of protuberances are designed on soil-engaging surfaces, the latter two contacting areas will be decreased, thus soil adhesion will be decreased too.

(2) Proper geometrical morphology of soil-engaging surfaces is equivalent to exerting proper force on the soil nearby soil-solid interface. Therefore, proper solid surface morphology can keep the interface at the first stage in which the waterfilm develops slowly. At this stage, outer force overcomes the static attraction of soil particles to soil water, the waterfilm beyond contacting points tends to be thinner and becomes free water eventually, soil particles move close to each other. All these changes will result in increasing of soil cohesion force. Besides, at this stage, outer force does not lead to distinct increasing of interfacial adhesion between soil and solid surfaces.

By influences of both the above aspects, the condition under which the soil-solid adhesion occurs — soil-solid adhesion force is bigger than soil cohesion force—is easily destroyed.

3 Conclusions

(1) The state of interfacial waterfilm is the most intrinsical genesis of macroscopic adhesion force of soil, it can be described by the area and thickness of interfacial waterfilm. The analysis of this paper proves and supplements the current soil adhesion theory about the role of interfacial waterfilm in soil adhesion.

(2) The developing procedure of soil adhesion interface can be divided into three stages: the stage in which interfacial waterfilm increases slowly; the stage in which interface waterfilm increases rapidly and the stage in which interfacial waterfilm varies very slowly and gradually approaching its saturation state. In each stage, interfacial adhesion has different varying patterns. The three varying patterns of soil adhesion prove theoretically that the conditions under which soil adhesion develops can be destroyed by proper geometrical morphology designing of soil-engaging surfaces.

(3) Grey system theory is suitable for analysis of soil adhesion experiment. The grey correlation analysis of grey system theory can further reflect intrinsic tendency and characteristics of soil adhesion system compared with traditional mathematical analysis. With grey system theory, accuracy of experiment method and accuracy of data processing methods are uniform and harmonious. The results obtained by using grey system theory can be explained by soil nature, soil microstructure and so on, and are accordant with the main conclusions obtained by former qualitative analysis. All these prove that the analysis method taken in this paper is effective.

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