

# Research Article

# **Experimental Research on the Impact of Temperature on the Adhesion Characteristics of Soil-Structure Interface**

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Under the working condition of mud cake, the continuous action between the shield cutter head and the soil on the excavation surface can generate high temperature in the process of shield tunneling and excavation, which changes the characteristic of the adhesion between the soil and the cutter head to intensify the phenomenon of making a mud cake on cutter, finally leading to a vicious circle. To study the effect of temperature on the characteristics of the adhesion of the soil on the surface of the structure, the soil adhesive situation and adhesion force at different interface temperatures were tested through a self-made experiment device. According to the result, it was indicated that the moisture content has a significant effect on the adhesion force of the soil, and the adhesion force firstly increased and then decreased with the increased of the moisture content and reached the maximum value near the plastic limit moisture content. The adhesion force changes very gently when the interface temperature is low. When the temperature reached 50°C, the adhesion force continues to increase as the interface temperature continuously increases except for the soils with high moisture content; moreover, the interface temperature has a great influence on the content of soil adhered on the structure surface. As for the soil with moderate moisture content ( $\omega = 21.21 \sim 31\%$ ), this content of the adhered soil increased exponentially with the increase of interface temperature; this content firstly decreased and then increased when the moisture content was high. When the soil was dry, there was almost no adhered soil on the surface and the interface temperature had no effect on the adhesive situation. By comparing and analyzing the adhesion state of the soil on the surface of the structure, the influence of temperature on the adhesion characteristics is mainly reflected on the variation of the soil moisture content within the influence range of the interface, the variation of the energy required for the destruction of the adhesion interface, and the change of the location of the weakest antistripping plane induced by both before. This research can better understand the law of formation and development of mud cakes and provided a new idea of solving the problem of mud cakes on the cutter head.

# 1. Introduction

At present, China is in the period of great development of subway construction. As the main method of subway construction, shield method has been widely applied, with advantages such as little influence, high degree of mechanization, good safety, low labor intensity, and fast progress. However, when shield tunneling is carried out in complex stratum, especially in clay stratum, mudstone stratum, and other stratum rich in clay mineral particles, it often encounters the difficult problem of constructing mud cake with cutter head. The clay debris cutoff will adhere to the surface of the cutter head when the shield cutter head passes through the clay layer and forms solid or semisolid masses by the compaction of cutter head, then sticks to the cutter head and blocks it decreasing the penetration so that the efficiency of shield excavation reduces [1–4]. The adhesion of soil is one of the important reasons for the formation of mud cake on the surface of the cutter head [5–10]. The existence of mud cake will not only lead to the increase of the torque of the shield cutter, but also block the suction opening of the slurry discharge pipe, which will seriously affect the shield construction technology and construction safety. The treatment and repair of a

TABLE 1: Physical parameters of used clay soil sample.

Plastic limit, $\omega_p$	Liquid limit, $\omega_L$	Nonuniform coefficient	Dominant diameter/ $\mu$ m	Silt particle content/%	Clay particle content/%
21.26	37.5	7.52	47.87	66.92	7.38

series of construction problems, such as residue improvement, mud cake removal, shield system reconstruction, stop and open the tank operation, and risk prevention, will greatly increase the construction cost.

Under normal working conditions, the temperature of the shield cutter head is generally  $40 \sim 50^{\circ}$ C, but during the process of tunneling, especially for the composite stratum, the torque and total thrust of the cutter head increase significantly when the advance speed slows down under the function of the formation and growth of the mud cake, which results in the temperature of the cutter head is as high as  $400 \sim 500^{\circ}$ C or even higher [11–13]. This high temperature can arise the temperature of the soil contacting with the excavation surface and enhance the adhesion of the clay so that the soil moisture migrates and intensifies the formation of mud cakes, which further aggravates the phenomenon of mud cakes on the cutter head and forms a kind of vicious circle.

Many studies indicate that the moisture content and temperature of the soil have a great impact on the characteristics of the soil [14–21]. Considering the effect of the temperature mainly occurs at the interface of the cutter head and the excavation surface during shield tunneling, to obtain the formation mechanism and development law of shield mud cake and solve the common engineering problem of mud cake formation on the cutter head, it is necessary to understand the law of the influence of the increasing interface temperature on the adhesion characteristics of the soil. In this paper, the adhesion force between the soil and the metal structure surface and the amount of adhered soil at different interface temperatures were tested to obtain the law of the influence of temperature on the adhesion of the soil, which can better understand the law of the generation and the development of mud cake, providing an idea of solving the problem of mud cake on the cutter head.

## 2. Materials and Methods

2.1. Experiment Sample. The tested soil sample was remolded silty clay; the undisturbed soil was taken from the construction site of the shield tunnel under the D1N-TA04 standard of the North Extension Project of Nanjing Metro Line 1. The physical parameters of soil samples are shown in Table 1, and the gradation curve is shown in Figure 1.

2.2. Experiment Apparatus. A designed adhesive test equipment of interface temperature was manufactured to test the adhesion of soil to the metal interface under different temperatures, as shown in Figure 2. To reduce the influence of the lateral friction of the interface on the determination of adhesion and to make sure the soil fully connect with the interface, this experiment made a metal cone as the test specimen by referring to the research of other scholars [22, 23].



FIGURE 1: Grain size distribution curve of used clay soil sample.

The test cone was made of 304 stainless steels with an apex angle of 50°. The lower cone was 32 mm high and in contact with the test soil. The upper part of the cone was wrapped with a polyimide heating film to heat the test cone. The temperature controller supplied power to the heating film and collected the temperature of the cone by the negative temperature coefficient (NTC) temperature sensor embedded in the center of the cone. To ensure a better measurement of the temperature, the gap between the NTC temperature sensor and the cone was filled with silicone grease to conduct heat. The test cone was driven by the electric traction test device (Figure 3) to pull the upper sling to separate the surface of the test cone from the test soil.

The traction test device used in the experiment is shown in Figure 3. The pulse signal generator sent out a pulse signal according to the set rotation requirements. After receiving the pulse signal, the driver converted the pulse signal into an angular displacement and sent it to the stepping motor; then, the stepping motor rotated and generated a rotating torque. The rod was connected with the stepping motor, and a sliding block was adhered to the screw rod so that the rotation of the stepping motor was converted into the vertical displacement of the sliding block, and the electronic tension meter was fixed with the sliding block through the connecting piece to make its vertical displacement occurs together with the sliding block. One end of the connecting rope was connected to the force measuring hook of the electronic tension meter when the other end was connected to the test cone sling; thus, the value of the cohesion force can be collected by the electronic tension meter.

2.3. Soil Sample Preparation. After drying and crushing the undisturbed soil, it was sieved to retain the soil with the particle diameter of 0.5 mm or less and then added with water to the design moisture content and mixed evenly, used the method of applying the paste to fill the mixed soil into the soil box by several layers, and used a scraper to smooth the soil surface until it became flat; finally, a soil sample was made by standing for 24 hours with the plastic film wrapped. When



FIGURE 2: Adhesive test equipment of interface temperature.



FIGURE 3: Electric traction testing device.

the error between the measured moisture content and the designed value is less than 0.5%, it can be regarded that the soil sample is effective and can be used to test.

2.4. Experiment Design. In this test, soil samples with the moisture content of 19%, 21.21% ( $\omega_p$ ), 23%, 27%, 31%, and 35% were made, respectively. For each set value of moisture content, the required pulling force with the velocity of 5 mm/min and the adhered soil on the cone surface were recorded for soil samples with the temperature of 26.5°C (room temperature), 40°C, 50°C, 60°C and 70°C, respectively. The specific methods were as follows:

- Press the lower part of the test cone vertically and slowly into the soil and stand for 2 minutes; hang the upper sling on the connecting rope of the tension meter in the electric traction test device
- (2) Turn on the NTC temperature sensor and check the collection status of the temperature controller, set the temperature of the temperature controller to control the interface temperature, and turn on the polyimide heating film power to start heating the

interface; the temperature controller automatically cut off, and the interface stopped heating up when the heating reaches the set temperature

(3) Start the device of electric traction test, apply upper tension to the test cone to separate the test cone from the test soil, test the applied tension in the process of separating the cone surface from the soil, and record the situation of the soil adhered on the surface of the test cone

For each of the experiment above, there were not less than 3 parallel tests, and take the peak tensile force as the measured value of the total adhesion force.

## 3. Results

At the beginning of the test, the soil body began to rheology after contact with the tip of the test cone under the pressure. With the test cone entering the soil, the soil around the vertebral tip began to extend to the upper end of the cone and formed a contact surface with the test piece. The redistribution of soil particles and moisture in the soil led the contact area to gradually increase and begin to appear a water ring until a continuous water film was formed; then, an adhesion interface was formed [24, 25]. Applying a force in the opposite direction to the test cone, the adhesion interface was broken along the weakest antistripping plane. When the weakest antistripping plane appeared inside the soil body, these broken soil layers would adhere to the surface of the cone and move.

3.1. The Variation of the Adhesion Force of the Soil Samples with the Changes of Moisture Content. Six groups of samples with different moisture contents were carried out the interface separation tensile test. Considering there are two adhesion forces in the direction of normal and tangent and they mainly act on the contact surface between the metal cone and the soil, this research will use the applied tensile force during the separation of the soil from per unit area of the test cone surface as the measured adhesion force for analysis by referring to the existing research [26].

The variation of the adhesion force of the soil samples with the changes of moisture content is shown in Figure 4.



FIGURE 4: The curves of the change of the adhesion force with moisture content.

It was illustrated that the adhesion force of the five groups with five different values of interface temperatures increased rapidly with the increase of moisture content before the plastic limit ( $\omega_p = 21.21\%$ ), and the maximum value appeared near the plastic limit; finally, this force decreased with the moisture content increasing. When the moisture content was relatively high ( $\omega > 31\%$ ), the adhesion force gradually stabilized. This law was roughly the same as the study results obtained by other researchers [27–29].

It can be seen from the variation trend that the adhesion force was very low when the moisture content was high or low. The effect of the moisture content on the adhesion force was significant when the moisture content was between the liquid and plastic limits and closer to the plastic limit, greater the adhesion force was. The curves of the change of the adhesion force with moisture content almost coincided at lower interface temperatures (26.5°C and 40°C).

3.2. The Variation of the Adhesion Force of the Soil Samples with the Changes of Interface Temperature. The adhesion force on the per unit area of 6 groups of samples with different moisture contents was measured at five different interface temperatures ranging from 26.5 to 70°C. As shown in Figure 5, it can be seen that the adhesion force of each group varied little with temperature for the low interface temperature. When the interface temperature reached 50°C, except the soil with higher moisture content (31% and 35%), the adhesion force decreased to a certain extent; as the interface temperature continuously increased, the adhesion force of each moisture content group continues to increase when the temperature was greater than 50°C; under the condition of higher moisture content ( $\omega \ge 31\%$ ), the adhesion force

3.3. The Situation of the Surface Adhesion. After the interface separation in the above experiment, by weighting the soil adhered to the cone surface, the average amount of soil

adhered to the per unit area of the cone surface can be obtained. The relationship between the interface temperature and the amount of adhered soil is shown in Figure 6.

For each group of clay with different moisture contents, the amount of adhered soil after the interface separation was very small when the interface temperature was low  $(\leq 40^{\circ}C)$ ; the amount of adhered soil increased with the increase of the interface temperature when the soil moisture content was between 21.21% and 31%; when the interface temperature was greater than 40°C, the growth rate gradually increased while the adhesion amount increasing exponentially with the interface temperature increasing; when the moisture content was higher ( $\omega = 35\%$ ), as the interface temperature increased, this amount decreased with little soil on the cone surface. As the interface temperature continuously increased, the amount of adhered soil was very small; the amount of adhered soil slowly increased when the interface temperature was greater than 50°C; when the sample was at a lower degree of moisture content ( $\omega = 19\%$ ), there was almost no soil adhered on the cone and no effect of the interface temperature on the adhesion.

As shown in Figure 7, under the condition of low interface temperature and moderate soil moisture content, the amount of adhered soil was very small with a little flakelike soil mass adhesion after the test cone surface was separated from the soil body; when the interface temperature rose, the adhered soil began to adhere in the shape of blocks and gradually developed after the interface was separated; when the interface temperature reached higher value, the amount of adhered soil on the surface of the cone was large and took part of the surrounding soil away to adhere to the cone together.

When the sample was at the state of low moisture content, the soil was dry and loose [30] so that the amount of adhered soil was almost unaffected by the interface temperature.

When the soil was at the state of high moisture content, the soil was soft and flow plastic [31]; the adhered soil can adhere to the cone surface in a paste form after the interface was separated when the interface temperature was low; as the interface temperature rose, the adhered soil decreased and paste adhered soil disappeared; when the interface temperature was high, a large number of flake-like soil masses gradually adhered to the surface of the cone.

# 4. Discussion

As a complex physical system, the soil had the characteristics of cohesion and adhesion simultaneously [32]. Cohesion is the mutual attraction among soil particles, and adhesion is the mechanical behavior of soil adhering to the surface of other structures [33]. The adhesion of soil to the interface involved a certain depth of soil below the interface layer. When the interface separates, the energy required for separation and the position of the separation plane depends on the strength and location of the weakest antistripping plane. Therefore, within the influence range of the interface, the adhesion to the surface of the structure depends on the



FIGURE 5: The influence of interface temperature on adhesion force: (a) relative low moisture; (b) relative high moisture.



FIGURE 6: The relationship between the interface temperature and the amount of adhered soil.

dynamic variation of the cohesion and external adhesion of the soil at a certain depth.

Moreover, the cohesion and adhesion of soil are the results of the interaction among solid soil particles, water, and structural interfaces. From the view of thermodynamic point, due to the interaction between the force field of solid surface and water molecules, the structure of the water adjacent to the solid surface will become stable when liquid water contacts the solid surface, which means the bonding structure of the water adjacent to the solid surface increased and the energy decreased [34]. Because the water film among clay particles and the water film between the particles and the interface of the structure were at a low energy level, to get rid of the adhesion between solids, a certain force need to be applied to the adhesion interface to increase the interface energy to achieve tensile failure. The tensile failure force is usually related to the area, thickness, and energy state of the interface water film.

Therefore, within the interface influence range, the moisture content of the soil at a certain depth and the interface energy state affect the characteristics of the adhesion of the soil-structure interface.

4.1. The Impact of Moisture Content on the Adhesion Characteristic. The moisture content has the most obvious influence on the adhesion characteristics of the soil. When the soil moisture content is lower than the plastic limit, the soil is dry and loose, an annular water film appears on the contact point of the soil particles while the water films are not connected, and the water exists in the form of structured water [35]. Due to the large specific surface area of clay particles and its greater binding capacity with moisture than that between moisture and metal surface, the internal cohesion of the soil is greater than the external adhesion force between the soil and the outer surface, which makes the interface failure mainly occurs at the interface between the soil and the structure surface, and the external adhesion force of the soil controls the adhesion. Because the water film between the soil and the surface of the structure is independent and discontinuous at this time, the provided external adhesion force is very small which leads to the low adhesion force and a small amount of adhered soil on the macroscopic aspect. The water ring developed as the moisture content increased. When the moisture content reached the plastic limit, the water films between the soil voids connected and formed a network; thus, the water films between the soil and the surface of the structure began to become continuous leading the external adhesion force of the soil to become very large, which was manifested as a large adhesion and a very low amount of adhered soil. As the moisture content continuously increased, the water film became thicker, the effect of the solid surface on the middle part of the water film reduced and the energy was the same as that of the free water, and the external adhesion force gradually decreased [36, 37], which



FIGURE 7: The conditions of soil adhering to surface.

was manifested by the gradual decrease of the adhesion force and the low amount of adhered soil. When the moisture content was very high, all the voids in the soil body were almost filled with water, and the rate of the decrease of the adhesion force will slow down if the moisture content is furtherly increased.

4.2. The Impact of Temperature on the Adhesion Characteristic. The interface temperature also has a relatively obvious influence on the adhesion characteristics, which is mainly reflected in two aspects:

- The variation of the moisture content within the range of influence of interface with the migration of moisture and heat caused by the local heating [38– 41]
- (2) The increase of soil water energy and the decrease of the energy required for the destruction of the adhesion interface with the increase of the temperature of the interface within the influence range of the interface [42, 43]

For soil with low moisture content, when the interface temperature was low, the temperature gradient between the soil at the interface and the internal soil was low, and the soil moisture and interface energy within the influence range of the interface did not change much with limited influence on the adhesion force and the amount of adhered soil; when the interface temperature increased to about 50°C, the moisture migration caused by the temperature gradient force was still small while the soil moisture within the influence range of the interface did not change much. Considering the interface adhesion is mainly affected by the interface energy and the high energy at the interface, the external adhesion force is less than the internal cohesion of the soil under the same moisture conditions; so it behaves the broken at the interface. the small amount of adhered soil adhesion, and the decrease of the adhesion force comparing with the low interface temperature. As the interface temperature furtherly increased, the moisture migration caused by the temperature gradient began to become obvious [40, 41], and the pore water in soil voids within the influence range of the interface migrated to the interior of the soil (Figure 8). The moisture near the interface decreased while the cohesion force and external adhesion force increased. At this time, the characteristic of the interface adhesion was mainly affected by the moisture content of soil at the interface, and the adhesion force increased. Simultaneously, due to the conduction of the interface temperature to the inside of the soil, a high energy plane with moderate temperature and moisture content appeared inside the soil, which becomes the weakest antistripping plane because of small damage energy. As the interface temperature increased, the weakest antistripping plane developed from the interface to the inside of the soil (Figure 9), and



FIGURE 9: Development of failure plane.

the soil internal cohesion force on this plane was less than the external adhesion force; therefore, the damage gradually occurred from the inside of the soil during separation when the amount of adhered soil rapidly increased.

For soil with higher moisture content, because of the thicker of the water film and the small value of energy required for tensile failure, the increase in interface energy caused by the increase of the temperature had little effect on the adhesion of the soil, but the influence of soil moisture change was obvious. Affected by the interface temperature, for the soil near the interface, the moisture decreased and the adhesion force increased. The damage occurred from the inside of the soil, and the adhered soil increased when the adhesion force was greater than the cohesion force. When the moisture content of the soil was high, the soil was in a state of flow plastic, and the cohesion force was very small. When the interface temperature was low, the soil was easily damaged from the inside with the paste soil adhered to the contact surface; with the increase of the interface temperature, the moisture content of the soil decreased, the cohesion of the soil increased rapidly, the integrity of the soil at the interface increased, and the amount of the attached soil decreased. With the interface temperature continuously increasing, the soil moisture content at the interface furtherly decreased, and the external adhesion force of the interface increased; thus, the failure mode changed from interface failure to the failure of the weakest antistripping plane with higher moisture content inside the soil.

## **5. Conclusions**

By analyzing the test results and the phenomena above, it can be concluded that the moisture content and interface temperature all have significant effects on the adhesion characteristics of the soil-structure interface.

- (1) Moisture content has the most obvious influence on the adhesion force of soil. When the moisture content is less than the plastic limit, the adhesion force is very small; with the moisture content gradually increasing to the plastic limit, the adhesion force rises rapidly and reaches the peak value around the plastic limit. The adhesion force gradually decreases when the moisture content increases to the liquid limit
- (2) The temperature of the interface will affect the moisture content of the soil within the influence range of the interface so that the moisture content of the soil close to the interface is reduced and the adhesive force changes. When the interface temperature is low, the adhesion force of each group of samples with different moisture contents changes little with

temperature, except for the sample with high moisture content ( $\omega \ge 31\%$ ); when the interface temperature reaches 50°C, the adhesion force decreases. With the interface temperature continuously increasing, the adhesive force of each group continues to increase; under the condition of higher moisture content, the adhesion force increases slightly with the increase of interface temperature

(3) The temperature of the interface will affect the position of the weakest antistripping plane within the influence range of the interface and changes the content of adhered soil. When the soil moisture content is moderate ( $\omega = 21.21 \sim 31\%$ ), the amount of adhered soil increases exponentially with the increase of the interface temperature; when the soil moisture content is higher, the amount of adhered soil first decreases and then increases with the increase of the interface temperature. When it is relatively dry, there is almost no soil adhered on the metal surface after the interface is separated, and the interface temperature has no effect on the adhesion

Therefore, when the shield construction is through the clay layer, the status of cutter head should be monitored at any time. It is necessary to take timely treatment measures when the torque of the cutter head decreases, the thrust increases, and the propulsion speed decreases. Measures such as increasing the amount of bentonite injected into the cutter head and the soil chamber or adding cooling water into the drain hole of the cutter head can reduce the temperature of the cutter head and prevent the formation and deterioration of mud cake caused by the strengthening of soil adhesion due to the high temperature at the interface between the excavated surface and the cutter head.

# **Data Availability**

The data are generated from experiments and can be available from the corresponding author upon request.

# **Conflicts of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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