A new method of controlling excavation face balance by using cutter torque under the condition of a small head aperture ratio

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Abstract. When the penetration and head aperture ratio of a cutter head are small, much earth will be clamped between the cutter head and the excavation face. This clamped earth directly balances most of the pressure from the excavation face, instead of the slurry pressure in the head chamber. In this case, some operators of shield machines and large pipe jacking machines in China have begun to use a new method, through which the earth pressure balance state can be controlled by the cutter head torque, instead of the slurry pressure in the head chamber. In this study, we investigate the formation process and stress state of the clamped earth between the cutter head and the excavation face. Contrary to common explanations, our research shows that the cutter head torque is not caused by the “earth–steel” frictional force between the cutter head plate and excavation face. The average frictional force between them can be close to zero in some situations. The cutter head torque is usually caused by an “earth–earth” friction between the clamped earth and excavation face. We also treat the clamped earth as plastic soil, which flows from the excavation face, via the section filled by the clamped earth, to the head chamber. In this way, the relationship among the cutter head torque, earth pressure, and excavated velocity is determined. Results indicate that controlling the cutter head torque is equivalent to controlling the state of the clamped earth. This method can avoid the uncertainty and fluctuation of friction on the shield shell and shield correction.

Keywords: cutter head torque, clamped earth, small head aperture ratio

1. Introduction

According to previous research, the cutter head torque mainly comes from the friction between the cutter head and the palm face; it is generally calculated by the “steel–soil” friction between the cutter head and the excavation face [1]. However, the torque is greatly affected by the head aperture ratio and soil property [2,3].

In this study, the clamped earth between the cutter head and the excavation face is considered. The clamped earth directly suffers the pressure from the excavation face. A model is built to analyze the mechanical state of the clamped earth. The relationship between the cutter head torque and the internal pressure of the clamped earth is also revealed. We find that the “soil–soil” friction between the clamped earth and the excavation face should not be ignored under the conditions of small head aperture ratio and low penetration. Through the measured data, we study the fluctuation of the cutter...
head torque. The results indicate that the internal pressure of the clamped earth around the cutter aperture determines the advancing speed, and the internal pressure and advancing speed are controlled by the cutter head torque, rather than the thrust force. We also determine the reason why operators can control the balance by using the cutter head torque.

2. State of “the clamped earth”

The rotation speed and advancing speed of the cutter head determine the penetration of the cutter bit. For example, 12 rows of cutting bits exist on the cutter plate. When the cutter head rotates one sixth of a circle, the whole excavation face is cut for once by the cutter bit. If the average advancing speed is 30 mm/min, and the speed of the cutter head is 1.7 r/min, then the instantaneous penetration degree of the cutter can be calculated to be only 2.94 mm. We plot the diagram in Figure 1. A space always exists between the cutter head and the excavation face.

![Figure 1. The clamped earth between the cutter head and the excavation face](image)

As the cutter rotates, a group of forces act on the “clamped earth.” We list these forces as follows:

1. Force of the scrape cutter that pushes the “clamped earth.”
2. Friction from the excavation face.
3. Squeezing force caused by the increasing volume of the scraping.
4. Earth pressure on the excavation face that is usually the key of earth pressure balance.
5. Reaction force from the cutter aperture that concludes the scraping acceleration, friction on the cutter aperture, and the head chamber pressure.
6. Friction from the cutter plate, the direction of the friction force depends on the motion state of the “clamped earth,” which changes subtly.
7. Pressure from the cutter plate, which is the indirectly balanced part of the pressure from the excavation face. The direction of these forces is plotted in Figure 2.
Figure 2. Force system and the direction of the forces

Although we are familiar with the force system, determining the motion state is difficult. Nevertheless, through the analysis of its formation and evolution, we can come up with five characteristic motion states of the clamped earth: filling, emptying, circulating, fluctuating plastic, and consolidated states. The diagram is plotted in Figure 3.

Figure 3. Motion state and stress state of the segmentation unit

(1) Filling state: When the cutter just begins to advance, it moves slowly toward the excavation face and begins to rotate. At the moment, most of the debris, which are cut down by the cutting bit, do not directly enter the soil chamber through the cutter aperture but fill the space between the cutter head
and the excavation face. At the time, the fill speed of the soil debris in the clamped earth is faster than the discharge speed of it. We can define it as the filling state.

(2) Emptying state: When the filling speed of the soil debris in the clamped earth is slower than the discharging speed, part of the clamped earth will flow into the soil chamber through the cutter aperture. We can define it as the emptying state.

(3) Fluctuating plastic state: When the shield advances at a constant speed, the debris filling speed is equal to the aperture discharging speed. The state of the clamped earth fluctuates between the filling state and the emptying state. In this state, the friction between the excavation face and the clamped earth is transferred to the cut bit. The soil–metal friction between the cutter plate and the clamped earth is average to zero.

(4) Circulating state: When the slurry outlet or soil outlet is clogging, the soil debris in the clamped earth will begin to circulate between the head chamber and the clamped space.

(5) Consolidated state: When the clamped earth is consolidated on the cutter head, the friction between the excavation face and the clamped earth is transferred to the plate completely, rather than to the cut bit. No soil–metal friction is observed.

Special attention should be paid to the difference between the filling/emptying state and the over/under excavation. All the states mentioned above can be over/under excavation. For example, if the clamped space is half full, then whether the clamped earth is in the filling/emptying state, the excavation face is under excavation. In the same way, when the clamped space is full, and its internal pressure is higher than the passive earth pressure, then whether the clamped earth is in the filling/emptying state, the excavation face is over excavation. The key to the judgment of over/under excavation is whether the average internal pressure of the clamped earth is higher/lower than the passive/active earth pressure.

3. Stress analysis

Among the five states above, only the fluctuating plastic state and consolidated state are available for a constant advancing speed. Their debris filling speed is equal to the discharging speed. The shape of the "clamped earth" stays relatively stable in both states. The debris in the "clamped earth" is also stable. The deformation of the "clamped earth" is limited and small. On this basis, we can build a finite element model by applying the ABAQUS, which is used to analyze the internal stress in the "clamped earth."

First, we can analyze the fluctuating plastic state. The "clamped earth" in the fluctuating plastic state is more preferred to soft plastic or flow plastic than plastic. Its shear modulus is low. To facilitate the calculation process, we choose the middle section of the cutter and block the aperture. We treat it as a special case of the fluctuating plastic state. In the model, we can ignore the friction from the cutter plate. Through modeling calculation, we find that the stress is concentrated around the cutter aperture, as illustrated in Figure 4.

**Figure 4.** Calculation of the fluctuating plastic state

Second, we analyze the consolidated state. The "clamped earth" in this state is more preferred to solid plastic, which sticks to the cutter plate, than plastic. In addition, most of the friction from the excavation face is balanced by the stickiness from the cutter plate. The "clamped earth" is fixed on the cutter plate. The average stress is far less than the stress in the fluctuating plastic state. The ABAQUS calculation result is displayed in the stress cloud of Figures 4 and 5, revealing that the internal pressure of the clamped earth in the fluctuating plastic state is six times larger than it is in the consolidated state.

**Figure 5.** Modeling calculation of the consolidated state
4. Fluid analysis of stable advancing

From being scraped to being discharged, the debris “flows” through many places. The potential energy is converted and consumed. First, the scraped debris is in the space between the excavation face and the cutter plate. Second, the debris is squeezed into the chamber through the cutter aperture. As the cutter rotates, the debris spirals forward to the export. Finally, the debris is discharged out from the export. During this process, the pressure and flow velocity of the debris are changing and so is the total energy that concludes the potential and kinetic energies. In this study, we use Bernoulli’s theorem to express the energy state.

In the last section, the stress is concentrated around the cutter aperture in the fluctuating plastic state. It means that the internal pressure of the clamped earth around the cutter aperture is high. According to the calculation result, the internal pressure of the clamped earth in the fluctuating plastic state is 4–10 times higher than it is in the consolidated state in the different sections of the cutter. The pressure difference between the “clamped earth” and “head chamber” accelerates the discharging of the debris. During this process, potential energy is translated to kinetic energy.

Interestingly, the fluctuating plastic state can improve potential energy and facilitate the squeezing speed of the debris by the pressure concentrated around the cutter aperture. For the consolidation state, the clamped earth becomes the mud deposition on the cutter plate, and it will balance the friction of the excavation face. The pressure in the clamped earth is roughly equal to the average excavation face pressure, much less than the pressure in the fluctuating plastic state. Evidently, the mud deposition will not affect penetration but will affect the stress transfer in the clamped earth. We plot the diagram of the debris “flows” and its energy variation in Figure 6 at the same penetration.

![Diagram of debris flow](image)

**Figure 6.** Energy variation of the debris flow
5. Application: Analysis of tunnel

5.1. Data analysis of pipe jacking
In China, when the cutter aperture is small, handlers mainly control the pipe jacking by using the cutter torque or the cutter motor power. They adjust the jacking speed to stabilize the cutter torque in a certain rage. The mechanics parameters of pipe jacking are listed in Table 1. The data of pipe jacking come from the BEITANG ROAD Multipurpose Utility Tunnel Project, which crosses the expressway. Through the data, we find that the cutter torque is stabilized in a certain rage and can reflect the change trend of the jacking force, as illustrated in Figure 7. Through correlation analysis, we find that the correlation coefficient of the jacking force and cutter torque is 0.45.

| Ring number | Cutter torque (KN.m) | Cutter rotation speed (rpm) | Jacking force (T) | Friction on back shield and pipe (T) | Jacking Speed (mm/min) |
|-------------|----------------------|-----------------------------|-------------------|---------------------------------------|------------------------|
| 8           | 192.3                | 1.23                        | 724               | 279                                   | 444                    | 8                      |
| 10          | 215.6                | 1.43                        | 743               | 483                                   | 260                    | 8                      |
| …           | …                    | …                           | …                 | …                                     | …                      | …                      |
| 23          | 159.5                | 1.7                         | 800               | 432                                   | 368                    | 10                     |
| 25          | 174.8                | 1.7                         | 787               | 508                                   | 279                    | 10                     |

Figure 7. The data of pipe jacking

Table 2. Shield tunneling parameter

| Ring number | Advancing speed (mm/min) | Thrust force ($\times 10^4$ KN) | Cutter torque (MN.m) | Rotation speed (rpm) | Pressure around the cut ring (bar) |
|-------------|--------------------------|---------------------------------|----------------------|----------------------|-----------------------------------|
| 138         | 20                       | 4.6221                          | 2.55                 | 0.8                  | 2.61                              |
| 139         | 20                       | 4.5469                          | 2.44                 | 0.91                 | 2.59                              |
| …           | …                        | …                               | …                    | …                    | …                                 |
| 272         | 25.5                     | 5.5127                          | 2.95                 | 0.65                 | 3.29                              |
| 273         | 23.3                     | 5.2177                          | 2.29                 | 0.76                 | 3.29                              |

5.2. Data analysis of shield tunneling
Different from the above example, The shield tunneling handlers mainly control the shield tunneling by using thrust force. The data of shield tunneling in table 2 come from the WANGJIANG ROAD Crossing River Tunnel. In this case, cutter torque is only a secondary parameter. According to the theory in Sections 1–3, cutter torque can represent the condition of the clamped earth, directly affecting the discharge speed of the crushed debris.
Through correlation analysis, we find that the correlation coefficient of advancing speed and thrust is 0.52, and that of advancing speed and cutter torque is only 0.28. The coincidence frequency of the rise–fall between advancing speed and cutter torque is as much as 85%, compared with the 60% between advancing speed and thrust force, which can be reflected in Figure 9. In another shield tunneling project, the correlation coefficient of advancing speed and cutter torque is nearly 0.6, compared with 0.13 between advancing speed and thrust force.

![Figure 8. Data of shield tunneling](image)

![Figure 9. Coincidence frequency on shield tunneling](image)

6. Summary
We have the following conclusions:

1. When the penetration and head aperture ratio of the cutter head is small, clamped earth always exists between the cutter head and the excavation face. As the shield advances at a relatively constant speed, the cutter torque mainly comes from the soil–soil friction between the excavation face and the clamped earth.

2. When the clamped earth is in plastic state, the cutter torque can enhance the potential energy of the debris in the clamped earth. The pressure accumulates around the cutter aperture. The pressure in the clamped earth around the aperture becomes 4–10 times larger than it is in the consolidated state. The difference in high pressure can make it easy to discharge the debris into the head chamber. The discharged speed is determined by cutter torque, rather than thrust force.

3. The correlation coefficient and coincidence frequency of the rise–fall among cutter torque, thrust force, and advancing speed show that advancing speed is also determined by cutter torque, rather than thrust force. Whether in a long-term trend or an instantaneous response, cutter torque is sensitive to the state change of the clamped earth. It can also weaken the interference of excess pore water pressure on the excavation face and reflect the change in effective earth pressure.

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