Supporting Technology Analysis and Attitude Control Principle of MSJ5.8/1.6D Shaft Boring Machine

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Abstract. A double-layer fixed support structure, with four supporting boots on each platform is used in MSJ5.8/1.6D shaft boring machine to adapt to weak or fractured stratum. Under the stratigraphic conditions, 8 types of support forms are unbalanced. According to this condition, we analysed the specific construction conditions of MSJ5.8/1.6D shaft boring machine in this paper. Then under these construction conditions, we used the finite element simulation to obtain the stress distribution of the supporting parts of MSJ5.8/1.6D shaft boring machine for propulsion unit is optimized. The stress concentration phenomenon appears in the inside of the arc plate of the upper and lower parts of the frame structure. According to the construction technology of the MSJ5.8/1.6D shaft boring machine, the attitude measurement, the attitude adjustment and attitude adjustment threshold rules of the machine are determined.

1. Introduction
The shaft is one of the important projects of mine construction, although its construction only accounts for 5%-7% of the total sinking and driving project, the construction period is long which accounts for 40%-50% of the total construction period (Liu 2013). At present, the main method of shaft construction in mine is drilling and blasting. Which including boring blast hole with Umbrella-type drill or handheld pneumatic rock drill, filling explosives, installing detonators, connecting detonation line, blasting, loading rock by grab loader, bringing out the gangue by bucket, cleaning bottom artificially or using the excavating machine, steel bar binding, pouring concrete in formwork, cable extension, and locating hanging scaffold, etc. (Wan et al 2010). Currently, the shaft drilling is highly mechanized, but the construction is mainly suitable for alluvium, and it is rarely drilling in hard bedrock. Therefore, we developed the MSJ5.8/1.6D shaft-boring machine with inserted tooth hob, which increases the construction speed to 100m-200m per month.

MSJ 5.8/1.6D shaft-boring machine meets shafts with 5.8m in diameter. It needs a laneway at the bottom and a pilot hole with a diameter of 1.6m. For the construction environment, the MSJ5.8/1.6D shaft-boring machine requires the stratum rock condition crossed by the shaft is stable and the water inflow is small, or we reinforced the stratum to meet the above conditions. MSJ5.8/1.6D shaft-boring machine adopts a new type of mainframe structure in which the rotating driving part of the cutter head is embedded in the supporting parts in order to reduce the height of the main frame and the height of the unsupported shaft wall. The structure features are that the upper and lower parts of the rotating driving part of the cutter head have a "mouth" steel beam, and each "mouth" steel beam is equipped with four supporting cylinders, which support the boot plate on the rock surface. The upper and lower "mouth" steel beams are connected into a whole by four guide posts, which also act as the guide rail of
the rotary drive part of the cutter head to provide the torque reaction force. Therefore, the supporting parts have different supporting states according to different geological conditions. It is necessary to study the propulsion technology of MSJ 5.8/1.6D shaft-boring machine under different geological conditions. It is also necessary to study the influence of force on supporting parts with different supporting states of supporting cylinders under different propulsion technologies.

There are few relative studies on gripper shoes for shaft-boring machines. However, for TBM gripper, Yu et al. (2014) established the three-dimensional tunnel surfaces model by projection method to study the non-linear behaviour of normal contact stiffness of tunnel surface and supporting system of tunnel boring machines. Xie et al. (2015) discussed coupling relationship between loads on the cutter head of tunnel boring machine and contact stiffness of gripper shoes and rocks under complex geological conditions. In this paper, firstly, the construction technology and we studied technical parameters of MSJ5.8/1.6D shaft-boring machine according to different geological conditions, and then we used the FEM to check the strength of supporting-propulsion components according to the technical parameters under different construction technology to ensure the construction safety of MSJ5.8/1.6D shaft-boring machine.

2. Construction technology and main technical parameters of MSJ5.8/1.6D shaft boring machine

According to the slag discharge modes of shaft boring machines, they can be divided into the upper slag discharged shaft boring machine and the bottom slag discharged shaft boring machine. The upper slag discharge means that the shaft boring machine can be driven from top to bottom without other auxiliary engineer. During tunnelling, rock fragmented by drill is separated from the bottom of the shaft by liquid, mechanical or vacuum pump, and transported to the upper part of the shaft boring machine. Then, the debris is separated and transported to the ground by bucket. Or a pipeline can be used to transport fluid containing debris to the ground and then separate the debris from the fluid. The bottom slag discharged shaft boring machine requires underground roadway conditions, and uses the hole drilled by raise boring machine as guide shaft. In the process of tunnelling from up to down, the rock fragmented by drilling is slipped through the guide shaft and discharged to the bottom of the shaft. The MSJ5.8/1.6D shaft boring machine is a typical bottom slag discharged shaft boring machine.

From top to bottom, the MSJ5.8/1.6D shaft boring machine is as follows: 1) Hoisting equipment, including hoisting headgear and auxiliary steady vehicle, winch, drill pipe hoisting equipment, shaftbore lock, chuck and sealing plate, etc. 2) Multifunctional support hanging scaffold, bucket, drill pipe and cables and water pipes fixed on the drill pipe. 3) Control platform, including transformer, controller, operating table, monitoring system and guidance control system, etc. 4) Supporting components and cutter rotary drive part components. 5) Knife dish. The above mentioned plus guide shaft with a small diameter of 1.6m and rock debris transportation part form the construction technology of shaft boring machine, as shown in Figure 1.

During the construction by MSJ5.8/1.6D shaft boring machine, the interaction between the machine and rock mass is divided into two parts. Firstly, the rock breaking process of the cutter head requires the inserted tooth hob on the cutter head to contact the rock and roll on the rock surface to break the rock, which is the main function of the shaft boring machine. The second is the interaction between the boot plate of the shaft boring machine and the rock wall of the shaft side. The supporting boot plate fixes the main engine of the shaft boring machine in the shaft, and provides the thrust counterforce required by the shaft boring machine. The stability of supporting boot plate directly affects the guarantee of propelling force and the stability of the main engine in the construction process. The stability of the shaft boring machine affects the rock breaking efficiency of the cutter head and the driving speed of the shaft boring machine. Because the two parts are directly in contact with the rock surface, there are many unstable factors, which should be a major consideration in the development of MSJ5.8/1.6D shaft boring machine. MSJ5.8/1.6D shaft boring machine breaks rock by inserted tooth hob. The torque required for the cutter head to break rock is reduced by two stage planetary, one spur gear deceleration and finally transmitted to the cutter head through the spindle. The four propulsion oil cylinders propel the spur gear reducer and the spindles on the gearbox to
transmit the thrust to the cutter head eventually. The reaction force during tunnelling is generated by the supporting boots on the supporting components which support the shaft wall.

Figure 1. Drilling technology of MSJ5.8/1.6D shaft boring machine.

The supporting components of the shaft boring machine are used not only to fix the driving parts, but also mainly support to fix the shaft boring machine on the rock surface so as to provide the reaction force needed to push the cutter head forward. In TBM, according to the logarithm of the supporting boots, there are two forms of horizontal support and X type support. Among them, the two supporting boots of the X type support can work independently, and the two supporting boots can move relatively. The use of this structural form in the shaft boring machine is conducive to cross the broken zone, which increases the stability of equipment and the adaptability of shaft bore. Therefore, on the basis of the X type support structure, this paper studies the project of supporting components of shaft boring machine.

The supporting boots of MSJ5.8/1.6D shaft boring machine are designed as four pairs of "cross" supporting boots. The driving distance of the shaft boring machine is 1.0m and the drilling speed is 0.5-0.7m/h. Thrust (Ts): refers to when the shaft boring machine support to the shaft, it can apply rock breaking propulsion along the thrust axis to the drilling bit. The total thrust of the shaft boring machine is designed as 6,000 kN. The maximum speed of shaft boring machine is 5 r/min. Torque (Ms): When the rock uniaxial compressive strength is less than 150 MPa, the rated torque of shaft boring machine is 500 kNm and the maximum torque required for the shaft boring machine to get out of difficulty is 1,000 kNm.

According to the two different quantities of force balance and moment balance, the actual designed supporting force must be greater than any one. For hard rock, the force of the supporting boots must be designed mainly by thrust. But for soft rock or fractured rock mass, under the premise of ensuring normal construction, the torque should be used as the controlled variable in the design.

Because the thrust acting on the boot of the shaft boring machine is large, accidents of instability of boot often happen during the excavation of the shaft boring machine. It is necessary to select out the type, length and width of the supporting boots according to the rock mass conditions in the process of tunnel excavation, so that the stress matches the rock mass conditions. According to the rock mass condition, the parameters of the shaft boring machine should be adjusted in time during excavation, so as to avoid the failure of the rock mass under the boots and the instability of the boots. The instability
of the boots will not only affect the rock breaking efficiency of the shaft boring machine, but also affect the overall construction progress of the shaft boring machine and delay the construction time.

3. Structural design of supporting components

The relationship between drilling pressure and penetration depth of TCT is closely related to the advancing speed and rock breaking efficiency of drill bits. From figure 3, the above three tip shapes have a deeper penetration tendency with the increase of drilling pressure, but the increasing amplitude is slightly different which is nonlinear. When the drilling pressure is small, the penetration increases linearly with the increase of drilling pressure. When the drilling pressure reaches a critical value, the sudden increase in the depth of penetration occurs. The phenomenon that the penetration depth does not increase uniformly with the increase of drilling pressure is related to the heterogeneity, anisotropy and brittleness-plasticity of rock. Moreover, when the TCT is penetrate into the rock with greater drilling pressure, the damage zone extends deeper into the rock and the penetration depth increases accordingly.

As shown in the three curves in figure 3, the penetration depth of the pick-shaped tip No.1 which with a smaller top circle is the largest, and the penetration depth of the pick-shaped tip No.2 is the smallest. The penetration depth of con-shaped tip, pick-shaped tip No.1 and pick-shaped tip No.2 is almost the same when drilling pressure is small. With the increase of drilling pressure, the penetration depth of pick-shaped tip No.1 deepens rapidly. When drilling pressure is bigger, the penetration depth of pick-shaped tip No.1 is far greater than that of the other two types. So it can be seen that pick-shaped tip No.1 has better rock breaking effect under larger thrust.

During the driving of a shaft boring machine, the supporting components are needed to fix the equipment first to provide the reaction force needed to push the cylinder to push the cutter head forward and the rotary reverse torque when the cutter head rotates. Therefore, the supporting components are the important parts needed for the normal operation of the shaft boring machine. The supporting components of the shaft boring machine are composed of a supporting cylinder, a supporting boot, a centralizer rod and a frame structure (as shown in Figure 3). Each supporting boot can be adjusted independently, and the distance between the two supporting boots is far, which is conducive to the shaft boring machine to find a favourable support point when passing through the broken stratum, increasing the stability of the equipment and the adaptability of the shaft.

When the supporting components are working, the supporting cylinder extends to support the boots on the rock wall, and completes the main engine fixed process, and at the same time transmits the reaction force and rotary reverse torque to the rock mass. In order to increase the frictional force between the supporting boot and the rock mass, anti-skid pins are arranged on the supporting boots.
Another function of supporting components is performing the directional control of shaft boring machines. In the process of shaft excavation, the posture of the main engine is adjusted continuously so that the shaft can be driven along the designed axis.

The propulsion system of shaft boring machine mainly includes propulsion cylinder and its auxiliary facilities. The propulsion cylinder is located on the upper part of the supporting components, connected to the driving device through the ball hinge, and eventually provides propulsion for the cutter head to push the machine forward. The maximum working pressure of the propulsion cylinder has been designed during the design and assembly of the equipment to meet the needs of rock excavation.

Because there are 8 boots of supporting components, as shown in Figure 3, and the whole structure is in an indeterminate state when they are supported on the rock wall at the same time, and it is necessary to calculate the structural strength of the frame structure by analysing the supporting conditions of the shaft boring machine. The supporting conditions of shaft boring machine include the following four parts: (1)Normal tunnelling. During the normal operation of the shaft boring machine, the maximum supporting force of the eight supporting cylinders is 1500kN. The supporting force is the same as that shown in Figure 2. The eight boots bear the same force as the ideal working condition, and the force is relatively simple. (2)Through the fractured zone. When the shaft boring machine passes through the fractured zone, two pairs of supporting boots are randomly extended according to the geological conditions, and the maximum supporting force may be exerted. (3)Rectify the deviation process. In the course of rectifying deviation, it is necessary to adjust the direction of the shaft boring machine, and fix the lower beam (or upper beam), and then adjust the central axis and angle of the whole shaft boring machine by adjusting the cylinder of the upper beam (or lower beam). (4)Unilateral support failure. For example, the upper horizontal beam (or the lower beam) is supported by only three boots, while the other one is not supported; the unilateral rock wall suddenly collapses; a single cylinder oil leakage failure and so on.

Therefore, in view of the above four conditions, the stress condition of supporting parts is simplified. Firstly, the working conditions of each cylinder are simplified as loading and unloading states, and loading means the maximum thrust of the cylinder is 1500kN, and unloading means the
cylinder does not apply thrust. The working conditions of 8 cylinders are simplified as follows: 1) All 8 cylinders are loaded. 2) The lower cylinder is not loaded, the upper cylinder is loaded. 3) 1, 3, 5, 7 cylinders are loaded, other cylinders are not loaded. 4) 1, 3, 6, 8 cylinders are loaded, other cylinders are not loaded. In these four cases, the calculation process of the supporting parts is as follows when the maximum thrust and torque are used. The safety factor of the supporting components under normal working conditions just meets the design requirements. So deviation cannot be corrected in the drilling, and only sweeping hole can be used to correct deviation.

4. Rectify deviation
In the course of rectifying deviation, it is necessary to measure the attitude of the machine first. Then adjust the attitude according to the measured results. At present, there are two schemes for adjusting the attitude of the MSJ5.8/1.6D shaft boring machine: A scheme is to adjust the attitude by changing the pressure difference of the supporting cylinder. However, in this paper, the deviation rectification of the machine by changing the displacement of the supporting cylinder is emphatically discussed. When the machine's attitude is adjusted to a certain value, it needs to decide whether to continue the attitude adjustment. Therefore, threshold rules need to be set.

A. attitude measurement
The possible relative position between the axis of the machine and the shaft centre line (Z axis) is shown in Fig. 4. Some of the attitude measurement instruments are the same as TBM. In addition, a horizontal inclination sensor is installed on the machine. Each supporting boot is equipped with a magnetostrictive displacement sensor, which can measure the extension value of the supporting boots.

B. Attitude adjustment
When the attitude of the machine needs to be adjusted, it is necessary to loosen all the support boots first. Then the support boots of the lower platform moves to 5-10 mm away from the shaft bore. Change the axis angle of the machine by adjusting the position of the hydraulic cylinder on the upper platform. Set the coordinate position of the cylinder as shown in Figure 3. No. 2 and No. 6 cylinders correspond to the positive direction of x-axis; No. 4 and No. 8 cylinders correspond to the reverse direction of x-axis; No. 3 and No. 7 cylinders correspond to the positive direction of y-axis; No. 1 and No. 5 cylinders correspond to the reverse direction of y-axis. The displacement sensor is installed on the supporting cylinder. The cylinder expansion can be adjusted only by the displacement D of the axis direction, the displacement angle theta of the axis direction and the angle of the inclination angle theta in the xy plane relative to the X axis.

C. Threshold rule of attitude adjustment
When the deviation occurs and exceeds the maximum deviation of the design, it is necessary to stop the machine to correct the deviation. In order to correct the deviation problem in time, it is necessary to set the threshold rule of attitude adjustment. The threshold rule of attitude adjustment includes the maximum allowable deviation threshold and the correction result threshold. Excessive setting of the maximum allowable deviation threshold value may result in excessive correction. This will increase the cost of rectification, and even exceed the rectification capacity of the shaft boring machine, which results in the abandonment of the shaft. If the value of the maximum allowable deviation threshold is too small, the machine will need to stop frequently to correct the deviation, which will affect the progress of excavation. The correction result threshold is related to the accuracy of laser, inclination sensor and magneto-induced displacement sensor installed on each supporting cylinder, and the servo control accuracy of supporting cylinder.

In the process of tunnelling construction, through its own guiding system, the displacement and deviation angle of the body axis relative to the design axis can be obtained. We discussed various of offset amount and angle, and worked out the rectification condition of the machine. When the deviation angle of the machine exists, the control system corrects the deviation reasonably according to the rectification algorithm. If the deflection angle is too large, such as exceeding the limit, the system should alert the operator to pay attention to the body deflection. When the axis of the block deviates from the design axis and its running trend deviates from the design axis, it is necessary to
correct the deviation in time and control the drilling route of the machine. When the offset is too large to exceed the maximum limit required by the project, in order to prevent engineering accidents, the machine should stop working and send technical personnel to conduct a detailed investigation of the deviation factors. If the geological conditions of surrounding rock are complex in practical engineering, it is difficult to ensure the complete coincidence of the design axis, and the attitude should be controlled within a certain range near the design axis, prevent excessive changes in the vertical degree of the shaft bore. At the same time, in the process of tunnelling, the future trajectory of the machine should be reasonably predicted, and the work should be stopped and checked in time before the offset reaches the maximum limit value, and the corresponding countermeasures should be taken.

![Figure 4. Deflection parameters of MSJ5.8/1.6D shaft boring machine.](image)

When the deviation is corrected only by moving the supporting boots, the mechanical analysis results show that the safety factor of the supporting parts is only 1.09 in the most dangerous condition because the cutter head receives the lateral force. Therefore, it is necessary to limit the thrust of the cutter head in the course of rectifying deviation. We set the maximum thrust to 50% of the total thrust. If the support boots can’t be used to correct the deviation in special strata, the hoisting equipment can be used to hoist the shaft boring machine, and the gravity can be used to correct the deviation by itself. It should be noted that the cutter head may be attached to rock fragments, and the centre of the machine may be slightly offset. So its accuracy is lower than that of correcting the deviation by supporting the boots.

5. Conclusion

Through the above calculation and analysis, we can see that when the supporting boots cannot support on the rock surface due to poor rock conditions or other reasons. The thrust should be reduced according to the rock conditions, or even be used to advance forward in the form of sweeping holes instead of directly driving down with the maximum thrust. There are two reasons: firstly, the design friction between the supporting boots and the rock surface does not meet the requirements, and can’t provide enough reaction for the maximum thrust; secondly, the strength of the frame structure requires decompress for drilling.

Through the finite element analysis, it can be seen that the stress concentration phenomenon appears in the inside of the arc plate of the upper and lower parts of the frame structure, and the stress value of the outermost stress curve is between 150 MPa and 267 MPa. Although the strength requirements were met, the dangerous area was strengthened in the later stage of design. Finally, through the secondary calculation, the overall safety factor is more than 1.5, and the structural strength meets the design requirements. In addition, the stress distribution can be optimized by adding braces after assembly, so the strength of the propulsion component can meet the design requirements.
According to the construction technology of the MSJ5.8/1.6D shaft boring machine, the attitude measurement, the attitude adjustment and attitude adjustment threshold rules of the machine are determined. We designed the deviation rectification scheme of support components of MSJ5.8/1.6D shaft boring machine. According to the measured deviation vectors, the attitude adjustment method was carried out by controlling the expansion of the support cylinder.

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