Experimental study on anchorage mechanism and performance of rock umbrella anchor

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Abstract: The existing reinforcement technology of rock slope and cavern cannot provide large anchoring force and high time efficiency at the same time, which leads to being unable to achieve rapid and effective prevention and rescue in case of landslide, collapse and other dangerous situations. As a new type of mechanical anchoring bolt, rock umbrella anchor is based on the principle of compressing rock mass by tensioning the metal wedge and then producing friction force, finally using the compressive strength of rock mass and interface action to obtain large enough anchoring force. The new anchor can adapt to the deformation of the rock mass, realize rapid anchorage, and obtain larger anchoring force while continuously tensioning. In this paper, the structure composition of rock umbrella anchor is introduced at first. Secondly, based on the geometric characteristics of the structure composition, the anchoring mechanism is analysed and supposed. Thirdly, in-door pull-out model test is conducted to study the structural and anchorage performance of the rock umbrella anchor. In the tests, the deformation characteristics of the anchor are recorded and analysed in the whole pull-out process. Meanwhile, the anchorage failure modes, failure mechanism together with corresponding bearing capacity are obtained, and the influence factors are analysed. Finally, the supposed anchorage mechanism has been verified and the suggestion for application of this new type of anchor is proposed. The results of this paper provide experimental support for the design and engineering application of rock umbrella anchor.

1. Introduction

At present, bolt technology is widely used in the field of rock mass anchoring, including grouting bolt, mechanical shell-expanding bolt and some new types of bolt [1–4]. Among these bolts, the anchorage body of the grouting bolt is formed by injecting grout into the borehole, and the anchoring force is provided by the bonding strength between the grout and the rock wall. While using the mechanical
shell-expanding bolt, the cone-shaped or wedge-shaped base at the bottom of the anchor head is screwed into the expansion shell to force them to open and invade into the rock wall to a certain depth through rotating the rod body. The anchoring force is provided by the friction between the opened expanded shell and the rock wall.

Studies on the failure mode and mechanism of grouting bolts and mechanical shell-expanding bolts have been reported quite widely in the literature. There are four main failure modes of grouting rock bolt, which are bolt rod fracture, sliding between bolt body and grouting body, interface sliding between rock mass and grouting body and rock failure [5]. Based on the in-situ pull-out test results of 181 rock bolts and cables in Sydney sandstone and shale area, Salcher and Bertuzzi [6] discussed the failure characteristics of bolts and cables. For the failure mode of the bolt rod fracture, the structural performance of the bolt can be judged by laboratory test, and the weak part can be found out. Zhang et al.[7] carried out the indoor structural performance and underground anchoring performance experimental research on the new type of recoverable mechanical shell-expanding end-anchored bolt. The indoor failure mode obtained from the experiment is the fracture of threaded section of the bolt rod outside the contact part between the wedge body of the anchor head and the rod body. For the failure of the interface between the anchor and rock, You et al.[5], Fang and Jiang et al. [8] studied the mechanism from the point of view of micro failure.

For the failure mode of rock mass in anchorage section, there are many assumptions about the shape of fracture surface [9], including conical surface [10-12], arc shape [13], linear and logarithmic spiral compound type [14,15], etc. Yang et al.[10,11] carried out in-situ test research and finite element simulation analysis on rock bolt foundation under different rock mass conditions. It is found that in general rock mass of class III and good rock mass of class II, the vertical angle of fracture surface of inverted cone is less than 10°. And the inverted cone failure zone is located above 1/2 of the anchorage depth in class III rock mass and above 1/3 of the depth in class II rock mass. Below the inverted cone failure zone is a small cylindrical failure zone surrounding the anchor foundation. He et al. [16] assumed that the inner end of the fracture surface is tangent to the anchorage section, and the top of the anchorage section is at a certain angle with the horizontal plane. Based on these assumption, a curved fracture surface equation is given determined by a two-parameter power function, which included a variety of fracture surface equations previously assumed. Through model test and numerical analysis, Zhang and Wu et al. [17] pointed out that the tensile and shear failure surface of inverted cone platform tunnel type anchor is a circular mesa with outward diffusion.

There are many researches focus on grouting bolt, but the cement mortar and other grout used in grouting bolt need a long time to achieve the expected strength, which cannot provide the anchoring force immediately. Generally, the depth of the drilling hole is large, the time cost for solidification make the efficiency of emergency reinforcement low. As to the mechanical expanded shell bolt, the expanded shell cannot be further opened in the process of use, and its radial extrusion force on rock mass is nearly unchanged. It can only use a small part of the compressive strength of rock mass, which makes its uplift bearing capacity is low.

To make full use of the compressive strength of rock mass and realize rapid anchorage, in this paper, a new type of mechanical anchoring bolt, rock umbrella anchor [18] is introduced. Firstly, the structure composition of rock umbrella anchor is introduced. Secondly, based on the geometric
characteristics, the anchoring mechanism is analyzed and supposed. Thirdly, in-door pull-out model test is carried out to investigate its anchorage performance. At last, the supposed anchorage mechanism is verified and some suggestions for application are proposed. The results of this paper provide experimental basis for the design and application of rock umbrella anchor.

2. Structural composition and assumption of anchoring mechanism 

The rock umbrella anchor [18], shown in Fig.1, consists of anchor head and anchor rod. The anchor head is composed of wedge-shaped prismatic sliding block, bearing block with cylindrical surface and guide block. In one anchor head, there are one sliding block, four bearing blocks and one guide block. During the installation, the casing pipe is put against the top of the anchor head, and the sliding block is pulled to make the bearing blocks open along the radial track in the guide block until they contact with the rock. At the same time, the shrinkage sliding of the bearing block is limited, and the friction between the bearing block and the rock wall is used to provide the anchoring force.

Base on the structural characteristics of the rock umbrella anchor, its anchoring mechanism is supposed as, the pull-out force of the bolt is transformed into the compression force and friction force of the bearing blocks on the rock mass through the wedge. The maximum friction force between the anchor head and the rock mass interface is the interface extrusion pressure multiplied by the maximum static friction coefficient. Therefore, the anchoring force can be always less than the maximum static friction force of the interface by setting the wedge angle of the sliding block. That is, there is no relative sliding of the interface and the anchor can be anchored. The larger the force of the bearing blocks compressing the rock mass, the greater the maximum static friction on the interface, and the larger the anchoring force can be obtained. The magnitude of anchoring force depends on the compressive property of rock mass. Therefore, it is practicable to use rock umbrella anchor to apply quick anchoring of rock mass.

Meanwhile, considering that the physical and mechanical properties of concrete and rock are similar, rock umbrella anchor can also be used for the reinforcement of concrete structure, which also has the advantages of high timeliness and high anchoring force.

3. Experimental investigation of rock umbrella anchor 

To verify the assumption of anchoring mechanism of rock umbrella anchor, an experimental investigation of the pull-out failure mode of the anchor was carried out in this study.

3.1. Test specimen 

The geometric parameters for the anchor specimen tested are listed in Table 1.

| Specimen | Closed diameter (mm) | Maximum opening diameter (mm) | Height of bearing block (mm) | Maximum opening distance | Diameter of rod at the head (mm) |
|----------|----------------------|-------------------------------|----------------------------|--------------------------|---------------------------------|
| 1        | 60                   | 68                            | 153                        | 83                       | 20                              |

In the test, the rod of the anchor head was connected with deformed steel bar through sleeve. The length of the deformed steel bar is 1300 mm, while its diameter is 25 mm as shown in Fig. 3.
3.2. Test and loading devices

A 1m × 1m × 1.5m reinforced concrete cuboid was used in the experiment to replace the rock block to test the anchorage performance of the rock umbrella anchor. In the center of the cuboid, a hole with diameter of 64 mm were reserved during fabrication. It was estimated from the preliminary
calculations that the reinforced concrete cuboid cannot fail during the pull-out test, with using C40 concrete and HRB 335 steel bar.

The pull-out load was applied using a through hole jack with a capacity of 300 kN. The jack was set on the top of the reinforced concrete cuboid, with the deformed steel bar passing through the hole. The deformed steel bar was fixed by taper clamp on the top of the jack, as shown in Fig. 4 and Fig. 5.

3.3. Test measurements
Tension coupon tests for determining mechanical properties of the steel were carried out for two groups of bar specimens: one group having a diameter of 20 mm representing for the rock umbrella anchor and the other having a diameter of 25 mm cut from the deformed steel bar. The results for specimen material are shown in Table 2.

| Group | Represent for                | Yield stress (MPa) | Ultimate stress (MPa) | Young’s modulus (GPa) |
|-------|------------------------------|--------------------|-----------------------|-----------------------|
| 1     | rock umbrella anchor         | 335                | 638                   | 205                   |
| 2     | deformed steel bar           | 330                | 611                   | 201                   |

To measure the pull-out displacement of the bolt, a dial gauge was located at the top of the deformed steel bar, as shown in Fig. 5. The measured range of the dial gauge is from 0 mm to +50 mm, covering the displacements predicted by the preliminary analysis.

3.4. Test results
The test results are shown in Fig. 6 as variations of the pull-out displacement $s$ with the load $P$. However, the displacement $s$ measured in the test includes the extension of both the deformed steel bar and the rod of the anchor head. Therefore, the real displacement of the sliding block $s_r$ was calculated and also graphed in Fig. 6. In the calculating process, the displacement of the deformed steel bar is taken as elastic deformation.

It is shown in Fig. 6, there are three stages in the curve base on the changes of the slope of the curve. At the beginning of the loading, when the load is small, the displacement $s$ and $s_r$ increases rapidly with an increase of the load. Then, in the second stage, the displacement $s$ and $s_r$ increases slower and slower with the same increase of the load. Finally, in the third stage, the displacement $s$ and $s_r$ increases rapidly until the ultimate load is reached. The final failure mode is the fracture of the deformed steel bar at the location of the sleeve connection part, as shown in Fig. 7. Meanwhile, the rock umbrella anchor is firmly stuck in the hole, as shown in Fig. 8.

3.5. Results analysis
Based on the structural composition and test results, the three stages can be corresponded to three stress conditions. At the first stage, the bearing block is not in close contact with the wall of the hole, and there is sliding between them. The compression and friction force in the interface are not large enough to make the bearing blocks and the wall relatively static. With the load increasing, the bearing blocks are opening until the compression and friction force are large enough to anchor the head of the rock umbrella anchor. Then the stress condition comes to the second stage.
In the second stage, with the load increasing, the bearing blocks is compressing the hole wall more and more tightly. A same increase of the vertical displacement of the sliding block, represents for a same increase of the opening diameter of the bearing blocks. In the process of loading, a same increase of the opening diameter of the bearing blocks can obtain larger and larger compression force from the hole wall. The fitting formula of the curve in this stage is $P=0.0479s_r^{2.4128}$, while the fitting coefficient $R^2$ is 0.9989. That is, though the vertical displacement of the sliding block increases linearly, the anchorage force increases exponentially.

In the third stage, because the stress increases constantly, the steel bar yields and the plastic deformation increases rapidly. The slope of the curve become small, as the fitting formula of the curve in this stage is $P=7.9207s_r - 70.915$, while the fitting coefficient $R^2$ is 0.9965. Finally, the steel bar fractured and the ultimate load was reached.

Based on the fitting results of the curve, the mutation point of the slope between stage 2 and stage 3, with $P=151$ kN and $s_r=28.106$ mm, can be easily distinguished. It is obvious that, improving the bearing capacity of the steel bar, the bearing capacity of the rock umbrella anchor can be improved. The pull-out force of the bolt is transformed into the compression force and friction force of the bearing blocks on the reinforced concrete block through the wedge. And the anchoring mechanism assumed before can be proved to be right.

![Figure 6. Variations of load with pull-out displacement.](image1)

![Figure 7. Failure mode.](image2)

![Figure 8. Anchor in the hole.](image3)

4. Conclusion

This paper has introduced the structural composition of the rock umbrella anchor and investigated experimentally the pull-out performance of the anchor. It is found that the pull-out process of the rock umbrella anchor can be divided to three stages according to the relationship between the load and the pull-out displacement. They are sliding in the first stage, the pull-out force exponentially increasing in the second, and steel bar yields in the third. The anchorage force of rock umbrella anchor is provided by the compression and friction between the bearing blocks and the hole wall. The second stage shows that, the anchor can use the compressive strength of reinforce concrete and the interface action to obtain large enough anchoring force. However, the strength of the steel bar limits the bearing capacity
of the anchor. To make full use of the bearing capacity of the rock umbrella anchor, the strength of the connection and anchor rod should be greatly improved.

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