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Review on the Anchoring Mechanism and Application Research of Compression-Type Anchor

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Abstract

To apply the compression-type anchor to deep roadways, this paper analyzes and summaries the bearing mechanism, shear stress distribution of the grout body and engineering application of the compression-type anchor. The analysis shows that the compression-type anchor has the advantages of reasonable grout body stress form, high loading capacity, good corrosion resistance and durability. The analysis also indicates that further study on the stress distribution of the compression-type anchor's grout body and the design of a new compression-type anchor with high strength initial support, simple structure, and small diameter that is suitable for the surrounding rock in deep roadway engineering is necessary to apply compression-type anchor supporting technology to the deep roadway.

Keywords

Tension-Type Anchor, Compression-Type Anchor, Grout Body, Fixed End

1. Introduction

At present, the pre-stressed anchor support is the major form applied in deep roadway anchor support. Practice has demonstrated that whether an anchor can provide sufficient pre-tightening force is key to realizing active support, effectively controlling the deformation of the surrounding rock in the roadway, and improving the anchor supporting quality in the deep roadway, especially in roadway support under broken rock mass conditions. Grouting anchor measures can effectively improve the integrity of the surrounding rocks in the roadway and effectively enhance the cohesion and internal friction angle of the surrounding rocks [1] [2] [3] [4], thereby increasing the self-supporting ability of the surrounding rocks and significantly improving the roadway-supporting effect and quality. However, because the length of the free segment of the grouting anchor is usually quite short, the application of pre-tightening force is very limited [5] [6] [7], which fails to meet the demand of active support. Even if the pre-tightening force can be applied, it must wait until the grout body reaches a certain strength, which is a fatal defect for deep roadways that require timely and sufficient supporting strength at the initial phase of excavation. Meanwhile, after the application of the pre-tightening force, the grout body, which is already bound to the anchor body, is in a most disadvantaged stress state: the brittle materials of the grout body are under tension, causing the supportive effect of the grouting anchor to further decrease and even become invalid.

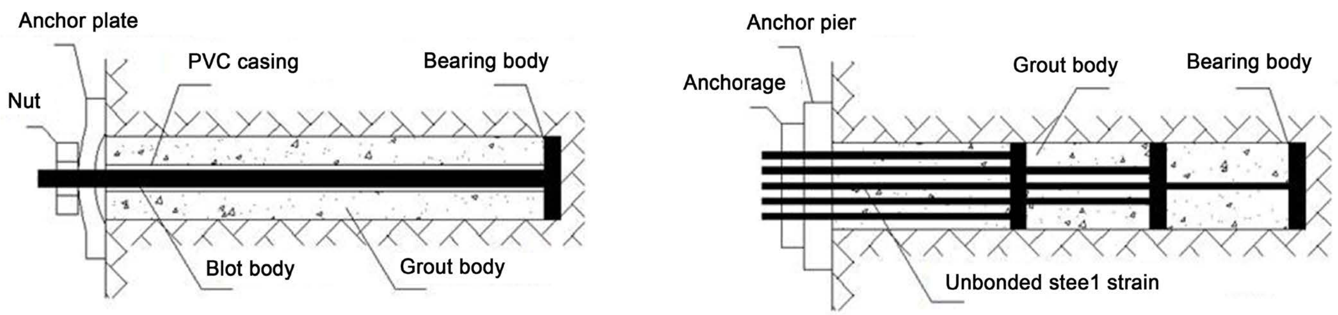
The currently used grouting anchors and resin anchors cannot simultaneously meet the demand for the anchor's high pre-tightening force, high-strength support at the initial phase, ability to fill fissures of surrounding rocks, and strong corrosion resistance and durability in deep broken surrounding rocks of the roadway support. Therefore, it is necessary to renovate the structure of the grouting anchor (tension-type anchor) to best maintain its active support effect, which will not only improve the integrity of the surrounding rocks but also provide a sufficient pre-tightening force at the initial phase of support and enable the brittle materials of the anchor's grout body to remain in an optimal compression state. Compression-type anchors have potential for this type of application; however, the available applications of compression-type anchors mainly include slope and foundation pit engineering [8] [9], and there is no report of its application in deep roadway supports.

Based on the research findings in fields including the anchoring properties of compression-type anchors and their application in slopes and foundation pits, through a systematic analysis of the reinforcement mechanism of compression-type anchors and their application, this paper aims to comprehensively understand the structural characteristics of currently available compression-type anchors, their stress features, the reinforcement mechanism of the surrounding rocks and its application scope and conditions. In addition, this work aims to clarify their advantages and disadvantages, provide guidance for applied research on their structural forms, improve their supporting performance, and provide support in the deep broken surrounding rocks of roadways.

2. Review and Analysis of the Bearing Mechanism and Functional Characteristics of Compression-Type Anchors

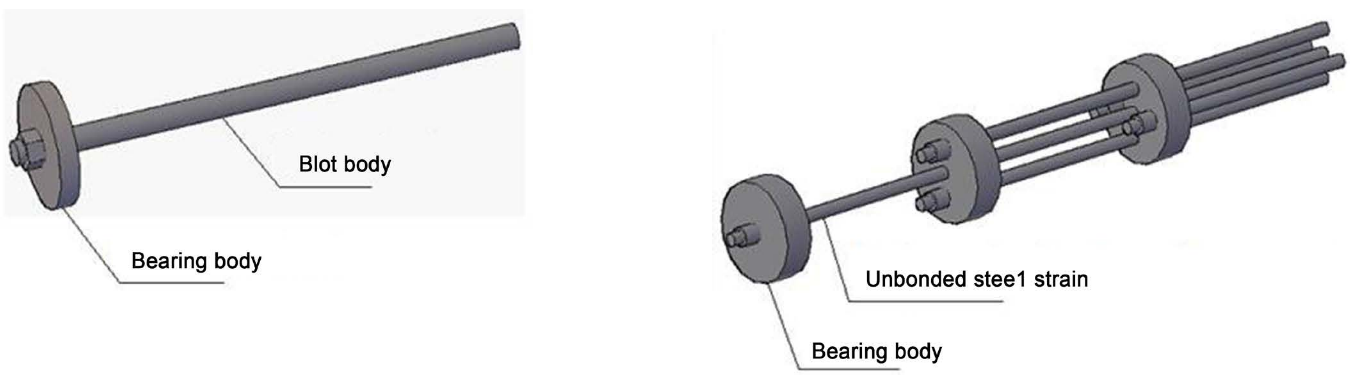
In the early 1970s, researchers proposed the concept of compression-type anchors to solve the issue of grouting anchors that were susceptible to corrosion [10]. In 1978, compression-type anchors received patent licensing in the US [11]. In the 1980s, Englishman Tony Barley first proposed the single bore multiple system (SBMA), which had an improved anchoring effect [12]. Compression-type anchors can be divided into compression-type and pressure-dispersive type. The anchoring structure and bolt body structure of each type is as indicated in **Figure 1** and **Figure 2**, respectively.

Compared with traditional grouting anchors, compression-type anchors have the following structural characteristics, as indicated in **Figure 1** and **Figure 2**.



(a) (b)

Figure 1. Schematic diagram for anchoring of a compression-type anchor. (a) Anchoring figure for a compression-type anchor; (b) Anchoring figure for a pressure-dispersive anchor.



(a) (b)

Figure 2. Schematic diagram of compression-type anchor structures. (a) Bolt body of a compression-type anchor; (b) Bolt body of a pressure-dispersive anchor.

1) The bolt body of a compression-type anchor is steel strand or PVC casing, which is unbound to the grout body.

2) The lower end of a compression-type anchor is a bearing body, which is unbound to the surrounding rocks near the bore bottom.

3) Pressure-dispersive anchors have several fixed ends and two steel strands that jointly anchor the rock and earth mass.

The load transfer mechanism of compression-type anchors is as follows: the anchor applies torque to exert tension, which is relayed via unbonded steel strain to the fixed end. The tension exerted on the fixed end is converted into the pressure on grout body, whereas a grout body under tension generates shear resistance to the surrounding rocks, thereby playing a role in anchoring the surrounding rocks [13]-[18].

The load transfer mechanism of pressure-dispersive anchor is similar to compression-type anchors, the difference is the tension of pressure-dispersive anchor being divided into several small load via unbonded steel strain which makes the stress distribution of the compression-type anchor's grout body more evenly.

Compared with the traditional tension-type grouting bolt, compression-type anchors have the following advantages:

1) The pre-tightening force that can be applied is significantly improved: the bolt body of the compression-type anchor is unbound to the grout body, and the grout body located between the fixed end and the anchor tray is under compression; thereby, it is relatively in tension. In addition, the tension-type anchor's grout body that is in a bound state with the anchor can apply and sustain a higher level of pre-tightening force. As a result, it can significantly improve the reinforcement and support of the surrounding rocks.

2) Its corrosion-resistance and durability are improved: the grout body of the traditional tension-type anchor is in a tension state, and because the grout body is made of brittle materials, it is apt to generate cracks under tension. The inroads of underground water generate corrosion, causing the durability of the grout body to significantly decrease. In contrast, the compression-type anchor changes the unfavorable working status of the grout body. Thereby, it has excellent anti-corrosion performance and durability.

3) Its bearing capacity is significantly improved: The anchoring effect of the traditional tension-type anchor mainly relies on the cohesive force between the bolt body and the grout body and between the grout body and surrounding rocks. However, because the brittle materials of the grout body are in a most disadvantaged tension state, the anchoring force that can be applied or provided by the anchor is very limited. In contrast, the brittle materials of the compression-type anchor's grout body are in a compression state that is conducive to its performance. As the compressive strength of the grout body and the shear strength between the grout body and surrounding rocks are increased, the anchoring force provided by the anchor is improved by a wide margin; thereby, the bearing capacity of compression-type anchor's grout body is significantly higher that of the tension-type anchor.

Compression-type anchors have the above-mentioned advantages in the reinforcement of surrounding rocks, which is needed in the current deep roadway anchor supports and unrealized by the traditional tension-type anchor.

3. Review of Research on the Stress Distribution of the Compression-Type Anchor's Grout Body

The manner in which the grout body relays the pressure (pre-tightening force) from the anchor's tray to the surrounding rocks is the key for the compression-type anchor to reinforce them. On the other hand, that which enables the grout body to effectively relay the pre-stressed load and enables the anchor to stay in an optimal working state is the key to realizing the active supporting effect of the anchor, which is also a focal issue that has been continuously studied by researchers.

3.1. Shear Stress Distribution of the Compression-Type Anchor's Grout Body

Based on studies on the mechanical rules of the traditional tension-type anchor's grout body [19] [20] [21] [22], the China Metallurgical Construction Design Institute firstly investigated the stress distribution of the compression-type anchor's grout body in 2000 in China [23]. Until now, the research results concerning the shear stress distribution of the compression-type anchor's grout body can be summarized as follows:

1) Based on Winkler's assumption on the stress distribution of the grout body, Cao analyzed and deduced the stress distribution of the compression-type anchor's grout body [24], namely, the shear stress of the grout body showed a hyperbolic curve distribution (**Figure 3(a)**) with its maximum value at the fixed end. As the distance from the fixed end increased, the shear stress tended to decrease and approached zero in the entire range of the anchorage segment.

The shear stress distribution of the compression-type anchor's grout body in **Figure 3(a)** was also confirmed by in situ experiments by some other researchers [25] [26] [27]. These studies showed that the grout body close to the fixed end was the maximum load location for the compression-type anchor, which was also the location that was prone to damage.

2) Stress distribution of the grout body based on Kelvin's assumption. Lu thought the stress state of the compression-type anchor's grout body could be simplified by the elasticity problem in which a point within the infinite body was acted upon by the concentrated force [28]. The stress distribution of the compression-type anchor's grout body was derived according to this conclusion combined with the Kelvin model. Namely, the shear stress of the grout body close to the fixed end was zero, rapidly arrived at its peak value within a very small distance from the fixed end, and then decreased to nearly zero within the 1/5 length of the anchorage segment, and the remaining length of the grout body did not sustain shear load (**Figure 3(b)**).

He's study [29] and Zhang's study [30] also further demonstrated that the shear stress significantly converged around the bearing body, which was consistent with the rule reflected in **Figure 3(b)**.

The stress distribution assumed by Kelvin shows that the shear stress significantly converges on the grout body around the bearing body, which is radically different from Winkler's assumed results. Based on this result, the length of grout body can be lessened,

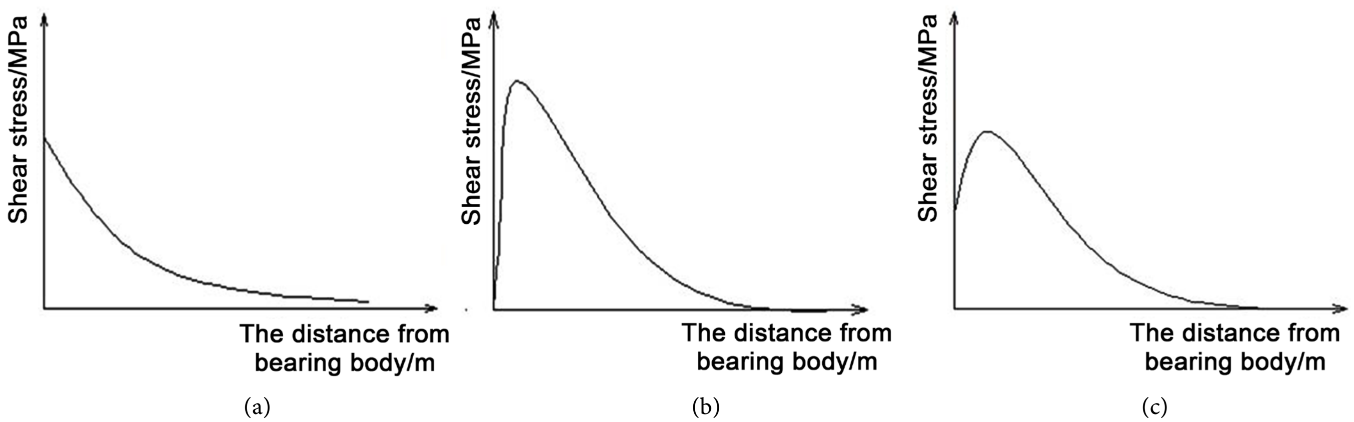


Figure 3. Stress distribution of the compression-type anchor. (a) Stress distribution based on Winkler's assumption; (b) Stress distribution based on Kelvin's assumption; (c) Stress distribution based on the modified Kelvin model.

which is significant to improve the project's efficiency and minimize investment.

3) Stress distribution of the grout body based on the modified Kelvin's model. Zhang analyzed the effect of the rock and earth mass within a certain scope around the anchor on the grout body's bearing and arrived at the stress distribution of compression-type anchor's grout body for the modified Kelvin's model [31], as indicated in **Figure 3(c)**. The numerical simulation in the literature also obtained the same results [32].

In **Figure 3(c)**, the shear stress of grout body close to the fixed end is neither equal to zero nor the largest value. It rapidly increases to its peak value after some distance. After that, the shear stress gradually decreases to zero with the increase in the distance from the fixed end at approximately 1/5 length of the grout body.

The shear stress of compression-type anchor under three different theories is completely different, it's because that under the Winkler's assumption, the shear stress of grout body is largest at the bearing body position; under the Kelvin's assumption, the shear stress of grout body is zero at the bearing body position; as for the modified Kelvin model, because of taking the residual stress of the grout body and the surrounding rock surface into consideration, the shear stress of grout body is not zero at the bearing body position, but the residual stress

Among these three types of stress distribution adjustment, the type that best conforms to the actual distribution of shear stress remains unknown; therefore, further research and analysis are needed in combination with theoretical analysis, actual measurement and other research methods to provide theoretical guidance for the effective application of compression-type anchors.

3.2. Shear Stress Distribution of the Pressure-Dispersive Anchor

Because the peak shear stress is close or near to the fixed ends grout body, the grout body at this location is apt to suffer shear damage, causing the anchor to become invalid. This phenomenon is the main defect in compression-type anchors. To solve this problem, Tony Barley proposed the pressure-dispersive anchor to improve the shear stress distribution and the working performance of the compression-type anchor [12].

In contrast to the structure of the compression-type anchor, the pressure-dispersive anchor is evenly distributed over a couple of bearing units divided by the fixed ends on the bolt body (**Figure 1**). The load sustained by the grout body of each bearing unit is far smaller than the peak load sustained by the compression-type anchor's grout body, thereby greatly lowering the possibility that the grout body is open to shear damage under the action of the peak load. The shear stress distribution for the loading units of the pressure-dispersive anchor is similar to that of the compression-type anchor in that there are also three types, as indicated in **Figure 4** [33] [34] [35] [36] [37].

The following conclusions can be reached by analyzing **Figure 4**:

1) Small peak shear stress of the pressure-dispersive anchor makes its ultimate bearing capacity higher than that of the compression-type anchor; therefore, the pre-tightening force that can be applied by the pressure-dispersive anchor to the supporting surrounding rocks is larger and can function better in active support.

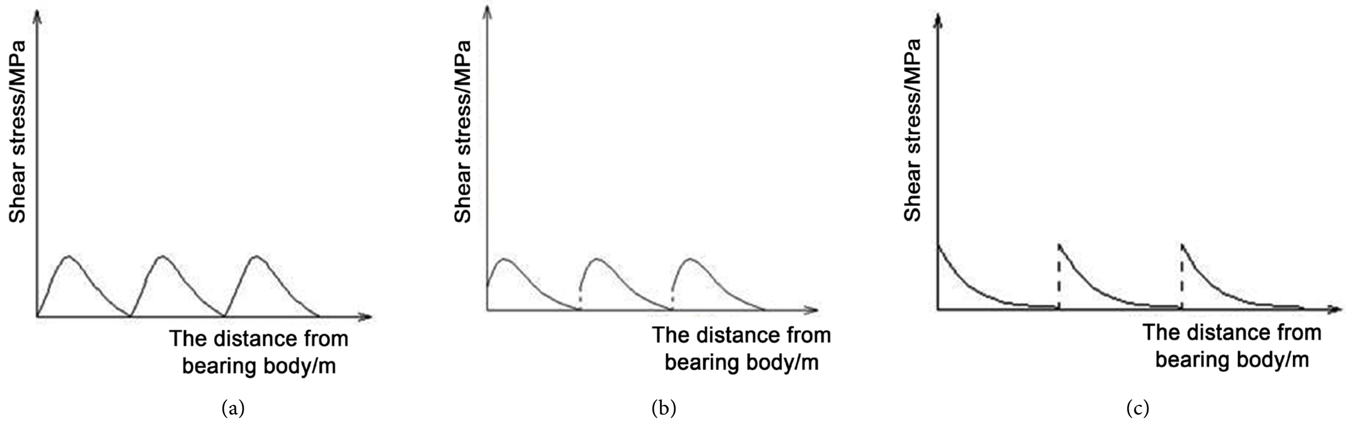


Figure 4. Shear stress distributions of the pressure-dispersive anchor. (a) Stress distribution based on Winkler's assumption; (b) Stress distribution based on Kelvin's assumption; (c) Stress distribution based on the modified Kelvin model.

2) The stress distribution of the pressure-dispersive anchor is even greater than that of the compression-type anchor, which can effectively avoid the deformation and damage phenomenon of the surrounding rocks caused by stress concentration and can activate the strength of the rock and earth mass within the anchoring scope for maximum support. This anchoring reinforcement effect is especially beneficial for the deep, weak and broken surrounding rocks.

4. Overview and Analysis of the Compression-Type Anchor's Engineering Application

The compression-type anchor (anchor cable) was initially applied in Southampton's Engineering in the UK in 1988 [38]. Later, Japan's KTB Society applied KTB pressure-dispersive anchorage technology in slope reinforcement engineering [39]. The compression-type anchor was first applied in foundation pit engineering of the Mansion of Bank of China, Beijing and achieved success [40].

Currently, the compression-type anchor has been extensively used in slope support, deep foundation pit support, dam foundation, and chamber reinforcement and anti-floating of foundations. Typical projects for the application of compression-type anchors are shown in **Table 1**.

The following conclusions can be reached by analyzing **Table 1**:

1) In both hard rocks of high strength or in soft rock and sand layers of low strength, compression-type anchors can sustain a relatively high anchoring force.

2) The compression-type anchor is mainly applied under the condition of shallow surrounding rocks, and its application in projects of deep surrounding rocks is not reported yet.

A small anchor pre-tightening force and weak active supporting effect is the main issues facing the current mine roadway support. Undoubtedly, properties such as good mechanical performance and rather high pre-tightening force for the compression-type anchor's grout body provide a new channel to solve the supporting issues for mine's

Table 1. Typical projects for the application of compression-type anchors.

Project name	Rock conditions	Cable-anchor parameters	Anchorage effect
The England new Dubin port sheet pile retaining wall support engineering [38].	In the dense to dense sand layer and gravel layer, the strength of rock and soil is high.	Unit level 4 anchor cable, the pressure-dispersive anchor anchorage length is 3 m, total length of freedom is 11.5 m.	The anchoring force of rock layer is 2000 KN maximum test bearing capacity is 5000 KN. The anchoring effect is good.
Changjin highway slope support engineering [41].	The upper is loess soil, the lower is weak rock mass, such as mudstone and sandstone.	The pressure-dispersive anchor space is about 3 m, the length is 15 m - 28 m.	The designing anchor capacity is 900 KN, the anchoring effect is good.
Beijing Hufeng mountain villa slope stabilization engineering [42].	Artificial soil filling layer, clay layer, strong weathering sand stone layer and weathered sandstone layer, etc. the strength of rock and soil is low.	Unit level 2 anchor cable, the pressure-dispersive anchor unit anchorage length is 5 m.	The bolt anchoring force is higher than 700KN, and it achieves the desired results.
Hong Kong airport underground station stabilization engineering [43].	The upper is sand filling, the lower is total disintegration granite.	The upper pressure-dispersive anchor is level 6 unit, the lower is level 7 unit.	The upper anchoring force is 1400 KN, the lower is 2000 KN, the anchoring effect is good.
The Singapore extremely soft sand rock stabilization e-engineering [38].	The strength of rock and soil is low.	Pressure dispersive cable with double-layer protection.	The anchoring force is 1600 KN, the anchor cable works good.
Beijing airport (expansion) underground garage anti-floating engineering [44].	Using jet grouting pile reinforcement sand and sand pebble bed, the strength of rock and soil is high.	Unit level 3 anchor cable, the pressure-dispersive anchor unit anchorage length is 3 m, 3 m, 2 m.	The designing anchor capacity is 230 KN, and it has a good supporting effect.
Guangxi long beach river Water complex project [45].	The dam foundation is weak interlayer, the strength of rock an-d soil is low, the structure is loose.	The pressure-dispersive anchor anchorage length is 3 m.	The project has been completed four years, the anchoring effect is good.

deep roadways. However, this technology has no application precedent in deep roadways. Therefore, it is necessary to research compression-type anchor technology featuring a high initial pre-tightening force, high supporting strength and good bearing performance of the anchor supporting structure suitable to the demand of deep roadways by combining the project characteristics of the deep roadway support.

5. Conclusions and Prospects

With its unique structure and bearing mechanism, the compression-type anchor displays better working performance in aspects such as good bearing performance in structures, high bearing capacity, corrosion-resistance and durability compared with that of the tension-type anchor and is extensively used in slope and foundation pit support engineering. However, in terms of the rather strong initial support strength required at the initial cut stage of deep roadways, the following studies are needed to apply compression-type anchors to deep roadway support.

1) Structural changes of the compression-type anchor are needed to enable it to provide high support strength for the roadway surrounding rocks at the initial support

stage. The compression-type anchor's fixed end that is currently available is unbound to surrounding rocks. Only after the cement mortar injected into the anchor holes reaches a certain strength can it exert a pre-tightening force on the anchor. In general, this period can be as long as approximately 20 days. However, at this time, the deep roadway's surrounding rocks may be seriously deformed. Therefore, this issue is a primary concern that must be solved in order to apply compression-type anchors to deep roadways.

2) Research on pressure-dispersive anchors with small-bore diameters suitable for the support of the deep roadway surrounding rocks is needed. The biggest advantage for the pressure-dispersive anchor is that it can reduce the peak load of the anchor's grout body by a wide margin, which can ensure the normal function of the anchor's support effort in its service life. However, pressure-dispersive anchors (anchor cables) applied in the support of foundation pits and slope engineering have complicated structures, large bolt diameters, and large amounts of consumed material, making them unsuitable for deep roadways in extensive need of anchors.

Therefore, it is necessary to identify new types of pressure-dispersive grouting anchors with simple structures, small diameters, and small amounts of consumed material that are suitable for the demands of deep roadways based on the excellent anchorage performance of the currently available pressure-dispersive anchor. Also, at present, there are three distribution patterns for grout body shear stress, and the one that best matches the actual stress state of the compression-type anchor's grout body remains unclear. Investigations into this issue will provide significant guidance for the rational design of the grout body's length, bore diameter and fixed end structure.

The study and breakthrough of the above-mentioned issues for compression-type anchors will provide new anchorage materials and technical means for deep roadway support and will also greatly promote the advancement of geotechnical engineering theory and application technology.

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