Analysis of shear characteristics of prestressed anchor cable and shear resistance of anchor joint plane

Zhao Yufei¹*, Nie Yong¹, Wang Wenbo², Jiang Long¹

¹ China Institute of Water Resources and Hydropower Research (IWHR), Beijing, 100038 China
² Sinohydro Bureau 6 Co., Ltd., Shenyang, Liaoning, 110179 China
*Corresponding author. E-mail: zhaoyf@iwhr.com (Zhao Yufei)
ORCID: https://orcid.org/0000-0002-7815-9332

Abstract: Reinforcing a high and steep rock slope is important in a water conservancy project. Accordingly, a prestressed anchor cable is the most commonly used slope reinforcement technology. In relevant standards, the prestressed anchor cable is considered as a tensile structure. In practical engineering, prestressed anchor cable is subjected not only to tensile load, but also to shear load. In this study, a large indoor direct shear test was designed to examine the shear characteristics of a jointed rock mass and the shear rupture rule of the prestressed anchor cable. The shear tests of different anchorage modes (i.e., full-length bond and full-length non-bond), different vertical normal stresses, and different prestress were designed. The results show a significant difference in the shear displacement curves between the full-length bonded anchor cable and the full-length unbonded anchor cable during shearing. The vertical normal stress and the prestress can effectively improve the shear strength of the joint in the front period; however, the higher the prestress, the smaller the shear displacement when the anchor cable is destroyed. The damage of the two types of prestressed anchor cables is basically the same and occurs first at the plastic hinge position.

1. Introduction
A prestressed anchor cable is commonly used as a means for rock mass reinforcement. It can reinforce deep rock mass and increase the rock mass integrity and has a higher bearing capacity than other reinforcement methods [1]. With its wide application, the anchor cable has gradually become the main support means for high and steep rock slopes, large deep foundation pits, and complex deep chambers. With the project usage and external environment constantly changing, the deformation of the anchored rock mass is inevitable. This will lead to the original support strength change of the reinforcing system and may lead to anchor cable fracture. According to field investigation, the rock mass deformation not only leads to prestressed anchor cable axial tension but also produces a transverse shear effect on the anchor cable [2, 3]. For the reinforcement of a rock slope with a structural plane, the unstable rock mass will slide along the structural plane and the rock mass will have a strong transverse effect on the anchor cable. Therefore, the sliding and shear resistance of the anchor cable should be considered when evaluating the anchor cable strength.

Many scholars are currently studying the transverse shear action between the anchor bolt and rock mass. Dulascka [4] believed that plastic hinges would be formed at the maximum bending moment point of the bolt under shear load and proposed the theoretical derivation of the shear strength of the joint plane. Fuller [5] proposed a mathematical expression for calculating the shear strength provided by a bolt. Meanwhile, Ferrero [6] studied the influence of the rock mass and bolt parameters on the shear properties of bolted joints. Ge Xiurun [7] proposed a formula for estimating the shear strength of jointed rock mass with anchors by studying its shear characteristics. Wang Xiaogang [8] studied the influence
of bolt failure mode and pin action on the shear plane shear strength during the shear process. Teng Junyang [9] conducted laboratory shear test studies using concrete and rebar to simulate anchor jointed rock mass.

In general, the anchor cable shear test can be divided into single and double shear tests. The single shear test is widely used, but due to the test equipment limitation, it cannot simulate the real situation very well. The double shear test, which uses asymmetric mode to perform the shear test, has obtained some research results, but it lacks a more in-depth analysis. In addition, a large number of the model tests have focused only on the bond bolt system, and only a few concentrated on the unbonded prestressed anchor cable. Considering the wide application of the prestressed anchor cable, an urgent in-depth research on the anchor cable shear characteristics must be conducted, and the mechanism of resistance to sliding and shear of the anchor cable must be revealed.

This study introduces a prestressed anchor shear test equipment. The influence of the anchor cable type on the shear characteristics is studied through different anchor shear tests. Moreover, the anchor cable in the shear failure mode process is elaborately presented. The shear characteristics of the prestressed anchor cables are investigated. Lastly, the deformation mechanism of the anchor cable, the slip resistance, and the shearing effect in the shear process are revealed.

2. Shear tests of the prestressed anchor cable

2.1. Test method and equipment

The study adopted the single shear test method to perform the test. Figure 1 shows a schematic diagram of the single shear test principle. In the test process, the anchor cable was used to reinforce the rock mass with a structural plane. Prestress was applied to the anchor cable, while vertical normal stress was applied to the rock mass. When the shear load was applied, the upper and lower parts of the rock mass slid relative along the structural plane until the anchor cable broke.

![Figure 1. Schematic diagram of the single shear test.](image1)

The equipment established herein (Figure 2) can apply the normal stress and prestress of the anchor cable, monitor the axial force at the end of the anchor cable, local stress, and strain state of the rock mass in real time, and perform the shear test of the anchor structural plane. The test system is mainly divided into four parts:

1. Test frame: This includes a reaction frame, a column, a test frame, and an internal metal frame structure.
2. Test model: This mainly includes concrete and anchor cable structures. The concrete structure size is 700 mm × 700 mm × 700 mm. The structural plane between two concrete blocks is used to simulate the structural plane of the rock mass. During the pouring process, a 6 cm-diameter hole is reserved to simulate anchor cable drilling. Two kinds of anchor cable (i.e., unbonded and bonded) were tested. The same steel strand was used as the rod material of the anchor cable. The steel strand used in the test was a Grade 1860 high-strength and low-plastic steel strand with 15.2 mm diameter. Table 1 lists the basic parameters.

![Figure 2. Direct shear test equipment.](image2)
### Table 1. Basic technical index of the steel strand.

| Tensile strength/MPa | Yield load/kN | Failure load/kN | Elasticity modulus/GPa |
|----------------------|---------------|-----------------|------------------------|
| 1860                 | 234.6         | 260.7           | 210                    |

(3) Load-applying equipment: This includes the horizontal and vertical load-applying equipment. The horizontal and vertical loads are controlled by two sets of independent static load testers (Figure 3).

![static load tester](image1)

![controller](image2)

![oil pump](image3)

![jack](image4)

**Figure 3.** Load-applying equipment.

(4) Sensors: The sensors used here are divided into four types (Figure 4), namely displacement, centering sensors (measure the anchor cable axial force), pressure sensors (monitor the horizontal shear load), and strain bricks (measure the concrete strain).

![displacement sensor](image5)

![centering sensor](image6)

![pressure sensor](image7)

![strain brick](image8)

**Figure 4.** Different sensor types.

#### 2.2. Test scheme and process

This test mainly studied the shear strength characteristics of a jointed rock mass reinforced by two types of prestressed anchor cables and the reinforcement mechanism of the anchor cables. Table 2 presents the test conditions. The main processes of the test are as follows: concrete test block casting; installation and tension of the prestressed anchor cable; installation of the instruments and the equipment; and mortar casting.

**Table 2.** Loading scheme for the shear test of the prestressed anchor cable.

| Loading scheme | Anchor cable type | Prestress/kN | Vertical pressure/kN |
|----------------|-------------------|--------------|----------------------|
| 1              | Unbonded          | 50           | 100                  |
| 2              | Bonded            | 50           | 100                  |
3. Analysis of the anchor cable shear test results

3.1. Shear load and anchor cable axial force–displacement

![Graph](image)

Figure 5. Shear load and axial force–displacement of the anchor cable.

Figure 5(a) depicts the relationship curve between the shear load and the anchor cable axial force to the displacement during the shear test of the unbonded anchor cable. The shear process can be divided into the five following stages:

1) Stage A: The displacement was unchanged. The structural plane and the mortar bore the shear load together. The axial force of the anchor cable was also unchanged. The grouting body was sheared broken when the shear load was increased to 53 kN.

2) Stage B: The end axial force of the anchor cable remained unchanged as the load was applied. The anchor cable also did not play the shear role. In this stage, the shear displacement reached 4.2 mm, while the shear load reached 58 kN.

3) Stage C: The anchor cable began to bear the shear load after the shear displacement reached a certain degree. The shear load rapidly increased to 149 kN. The axial force at the end of the anchor cable remained unchanged. The anchor cable showed a certain degree of bending deformation in the later stage.

4) Stage D: The anchor cable played the main role of the sliding and shear resistance. The anchor cable deformation was larger. The end axial force of the anchor cable slowly increased. The final shear force of the structural plane was 307 kN. The end axial force of the anchor cable was 190 kN. The test showed that the structural plane friction coefficient was 0.472, and the shear force obtained according to the conventional calculation method of the prestressed anchor cable was 190 kN × 0.472 = 91 kN. Meanwhile, the actual shear force was 307 kN, increasing by 216 kN. The conventional calculation method greatly underestimated the sliding and shear resistance of the prestressed anchor cables.

5) Stage E: Destruction.

Figure 5(b) illustrates the relationship curve of the shear load and the anchor cable axial force to the displacement during the shear test of the bonded anchor cable. The shear process is divided into four stages as follows:

1) Stage A: The displacement remained unchanged. The structural plane, mortar, and anchor cable bore the shear load together. The end axial force of the anchor cable also remained unchanged. The grouting body was sheared off when the shear load increased to 71 kN.

2) Stage B: The structural plane and the anchor cable contributed to the shear force together. The anchor cable produced a small shear deformation. The shear load increased to 164 kN. The axial force at the end of the anchor cable remained unchanged.

3) Stage C: The anchor cable played a sliding resistance and shearing role, resulting in a large bending deformation. The end axial force of the anchor cable increased. At this stage, the final shear force of the structural plane was 312 kN. The end axial force was 86 kN.

4) Stage D: Destruction.

3.2. Interaction between the anchor cable and the concrete

In the experiment, strain bricks were embedded in the concrete. Each strain brick was equipped with a sensor in two directions, with the shearing direction marked as H, and the vertical direction marked as
V. Figure 6 shows the variation of the horizontal and vertical strains with the increase of the shear displacement in the strain brick closest to the structural plane. The horizontal and vertical strains in the concrete sharply decreased with the increase of the distance from the structural plane. This shows that concrete deformation only occurs in a small range, and the closer to the structural plane and the anchor hole, the stronger the interaction between the rock mass and the anchor cable.

![Concrete strain curve](image)

**Figure 6.** Concrete strain curve.

3.3. Deformation and failure of the anchor cable and the concrete

3.3.1 Anchor cable deformation failure analysis

Figure 7 shows the fracture photos of different types of anchor cables damaged in the shear tests during the test. An observation of the fracture of several different anchors showed that most of the fractures had the same characteristics as the tensile fracture of the steel strand, including the zigzag structure at the fracture, necking phenomenon at the fracture, and characteristic zone of the typical ductile fracture.

![Fracture characteristics of the anchor cable shear failure and the local concrete deformation](image)

**Figure 7** Fracture characteristics of the anchor cable shear failure and the local concrete deformation.

3.3.2 Concrete deformation failure

Figure 9 displays photos of the anchor cable after the shear failure under different working conditions. With the shear load and shear displacement increase, the anchor cable underwent a bending deformation and interacted with the local mortar due to the shear force action. The steel strand will continue to squeeze the mortar on one side and cause its local deformation and failure. The other side of the mortar will be separated from the steel strand, eventually forming a half-bell shape.

3.4. Discussion

This study was conducted under only one prestress level. The increase in the shear strength during the shear process of the anchor cable was different for the other prestress conditions. It can be predicted that the initial shear strength of the structural plane will be relatively high when the prestress level is large. For example, the initial shear strength will reach 156 kN when the initial prestress is 200 kN. The shear displacement of the anchor cable during the shear failure will decrease as the prestress level increases, resulting in an incremental reduction of the shear strength of the structural plane in a later period.

The concrete strength is also an important factor affecting the shear strength increment of the structural plane. For example, the concrete strength is great in extreme cases. With the increase of the shear displacement, the anchor cable will not experience a bending deformation, and the axial force of the
anchor cable will not increase. The increment of the late shear strength can only be provided by the shear strength of the anchor cable itself. The proportion of increment of the late shear strength will also decrease accordingly.

4. Conclusion
In this study, shear tests of two types of anchor cables (i.e., unbonded and bonded) were performed to study their slip resistance and shearing effect. The main conclusions are as follows:
(1) When the anchor cable and the mortar are bonded together, their shear resistance can be exerted at the beginning of the shear, and their ultimate failure shear displacement is relatively lower than that of the unbonded anchor cable.
(2) The shear resistance provided by the anchor cable is divided into two stages: 1) shear resistance of the anchor cable itself; and 2) shear resistance provided by the bending deformation of the anchor cable. The prestressed anchor cable can significantly improve the shear strength of the structural plane of the rock mass with the anchor. The sliding and shear resistance of the anchor cable should also not be ignored.
(3) The anchor cable failure in the shear process is mainly characterized by the tensile failure. During this shear process, the partial concrete forms a cavity on one side, while the other side is squeezed by the anchor cable.

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