Experimental study on broaching self-locking anchor rod with mega prestressing force

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Abstract. In order to solve the problem of applying super-tonnage prestressing force to the gate pier in the process of dam reinforcement, this paper presents a comparative study on the three groups of test specimens of prestressed counterbore self-locking anchor rod and unbonded prestressed anchor cable. They show: (a) both methods satisfy the needs of applying prestress, the experiment conducted on the gate pier that is to be renovated has tested the prestress loss of two schemes and the concrete stress in both free section and anchor section after applying the prestress. The results and counterbore self-locking anchor rod boasts shorter anchorage section and better applicability. (b) the anchorage sections of two schemes generate additional tensile stress, and the maximum additional tensile stress in the anchor rod features 54% less than that of anchor cable, smaller range of additional tensile stress and more reasonable stress state of concrete than that of anchor cable.

1. Introduction

During the pre-design inspection of Danjiangkou Dam Heightening Project, many horizontal interlayer joints are found in the middle of the pier. After the calculation, the tensile stress area generated in the upstream end of the pier under the asymmetric stress condition (one side of the flood water is released and the other side of the spillway is closed) can crack the existing interlayer joints and affect the durability of the pier under the action of the vibration load induced by flood discharge. Therefore, it is proposed that vertical preloading stress will be applied to the pier to improve the integrity and durability of the pier. By calculation, 2000kN prestress needs to be applied to 5 locations of each pier distribution.

In the heightening project of Roseires Dam [¹] in Sudan, 10000kN prestressed anchor cables are used to reinforce the overflow dam. The length of anchor cables is 28m, 32m and the length of anchor sections is 15m. Prestressed anchor cables are used in the cracking treatment of Fengman Dam [²] with a maximum of 100kN for a single hole, and 3000kN for Panjiakou Dam [³] with an anchorage length of 9m. It is a feasible plan to reinforce concrete dam with prestressed anchor cable, but the anchoring length of the anchor cable is relatively long. Therefore, a self-locking anchoring prestressed anchor rod with inverted cone-shaped inner anchor head (a multi-layer broaching self-locking prestressed anchor rod and its installation method, ZL201610768558.3) has been developed for giant structure.
The principle is to expand the inverted conical hole in the designed anchoring area, and automatically open the inner anchor head to contact the top surface of the inverted cone after it is in place, so as to provide super-large anchoring force. In order to understand the performance of prestressed broaching self-locking anchor rod and common prestressed anchor cable, the following two plans are designed for comparative study in order to optimize the plan:

Plan A: The anchoring section adopts 3 layers and 6 PSB930 grade φ25 high strength finish rolled rebar, and forms mechanical engagement through inverted cone broaching to provide anchoring force. After the anchor rod is installed and prestressed, the whole process of free tensioning section is grouted to form a bond.

Plan B: The anchorage section of Plan B adopts three groups of load dispersion types, and depends entirely on the bonding of grouting materials to provide anchorage force. Fourteen 7Φ5 unbonded steel strands are selected for anchor rods. The anchoring section is grouted and solidified before tensioning and prestressing. There is no bonding between the free tensioning section and the grouting material.

2. Test Design

2.1. Specimen design

The test site is located on the pier of the dam to be reconstructed, and the design of the test pieces is shown in Table 1. Since the water surface is not more than 15m below the top surface, in order to study the concrete stress state of the anchoring section, the design depth of anchor rods 2 #, 3 #, 5 # and 6 # is shortened. The design depth of 1 # and 4 # is relatively long to understand the stress state of the free section after prestress is applied.

| No.  | Hole depth/m | Distance edge/mm |
|------|--------------|------------------|
| 1#   | 30           | 1000             |
| 2#   | 10           | 300              |
| 3#   | 10           | 500              |
| 4#   | 30           | 1000             |
| 5#   | 20           | 1000             |
| 6#   | 15           | 300              |

Plan A: The single-layer broaching self-locking anchor head test of 4 finished rolled rebar with 4m hole depth was carried out to provide data support for the design of Plan A. The maximum load of single-layer anchor head is 2034.1 kN (the stress of steel bar is 1056.0 MPa, the extension of anchor rod is 16.79 mm), and the instantaneous loss of prestress after end anchoring (the loss of prestress caused by anchorage deformation and the shrinkage of prestressed steel bar σl1) is 176.4MPa (the relative retraction is 2.69mm) with the prestress loss reaching 16.7%. After 8 hours, the reinforcement stress is 847.2MPa and the prestress loss is 32.4MPa. The anchoring force of a single anchor head can reach more than 2000kN. In order to avoid stress concentration, the inner anchor head is divided into 3 layers with a spacing of 3m. The design drawing of Plan A is shown in Figure 1 (a) and Figure 1 (c).

Plan B: As the inner anchor section relies on bonding to provide anchoring force, the stress distribution of the bonded inner anchor section is uneven. If the consequences of bonding failure are serious, it is optimized to be 3-layer dispersed bonding anchoring with an anchoring section length of 16m. The design drawings are shown in Figure 1 (b) and Figure 1 (d). For the anchor cable numbered 6#, since the hole depth is only 15m, the length of the anchoring section in each group of steel strands in Figure 1 (b) becomes 6m, and the spacing between each group of anchor heads is 3m. Other design parameters are consistent with Figure 1 (b).
2.2. Test materials
The measured maximum tensile design value of 1860 grade 7φ5 steel strand is 267.0kN and the elastic modulus is 1.93×10^5MPa. The measured tensile strength σ_t=1360MPa, yield strength σ_s=1220MPa and elastic modulus 2.06×10^5MPa of PSB930 grade φ25 finish rolled threaded steel bars.

Anchor head in broaching self-locking anchor rod: It consists of wedge and support, of which wedge is divided into 6 pieces. The bearing material is Q235B, and the wedge material is white cast iron. The outer diameter of the cylinder after the inner anchor head is assembled and closed is φ155 mm, the opening angle of the wedge after opening is 26.56 degrees, and the wedge length is 161mm.

ICG micro-expansion high-strength inorganic grouting material is prepared according to powder: water = 1: (0.26-0.28) (weight ratio). After 3 days of normal curing, the concrete strength reaches above C40.

2.2.1. Loading system.
In Plan A, the anchor rods of the bottom layer, the middle layer and the top layer are tensioned in turn. According to the test results of the ultimate bearing capacity of the single-layer anchor head, the prestress loss of anchoring locking reaches 16.7%. In order to meet the requirement of 700kN prestress in the test, 871.3 kN load corresponding to 12MPa oil pressure gauge is taken as the maximum tensile force. In Plan B, the total prestress of the anchor cable is 2100kN, which is over-stretched to 2200kN, and the tension of each steel strand is 157.14 kN, which is stretched in groups according to the free length. The load is applied continuously at one time, and the relevant experimental data are recorded at an integer multiple of 2MPa indicated by the oil pressure gauge.

2.3. Measurement contents
2.3.1. Load measurement.
Electric oil pump and YCW400B hydraulic jack are used for loading, and the load is controlled by the pressure gauge on the oil pump. Before the test, the jack calibration obtains the corresponding parameters of oil pressure and load. Measure the strain of the anchor rod in Plan A and the steel ring.
added under the top of Plan B to check the load.

2.3.2. Strain and deformation measurement.
Plan A: In order to study the distribution characteristics of anchoring force along the path of prestress in anchoring section and its influence on dam body stress, strain distribution under different anchor head prestress is obtained by pasting strain gauges along the dam body facing water surface during field tests. Strain gauges shall be arranged every 1m from 0.25m below the top surface to the water surface or the end, and additional strain gauges shall be added near the inner anchor head. In order to effectively monitor the stress of steel bars during tensioning, strain gauges are pasted on the side of steel bars 1.5m away from the orifice, and dial gauges are used to record the elongation during tensioning.

Plan A: Strain gauges are arranged every 1m from 0.25m below the top surface. During the tensioning process, the dial indicator is used to record the elongation during the tensioning process. At the same time, a force transmission sleeve is placed between the anchor plate and the support backing plate, and the prestress of the anchor cable after tensioning and locking is effectively monitored through the strain of the force transmission sleeve.

3. Test Results

3.1. Prestressed tension
Prestress monitoring of broaching self-locking anchor rod is shown in Table 2. When the anchor rod is locked with the reinforced dam body through the pre-tightening nut, the loss rate of corresponding steel bar stress is 15.1% ~ 17.6%. The first batch of prestress loss is related to the length of the free section of the anchor rod. The shorter the length of the free section, the greater the prestress loss, but it is not nonlinear. The prestress within 8 hours was recorded.

After anchoring, the prestress continued to lose, with more in the first 2 hours and gradually decreasing in the later period.

| No. | Free length /m | Tensile stress /MPa | Post-anchoring stress /MPa | Loss value /MPa | Phase I loss Rate | Tension length/mm | Retraction /mm | Stress after 8h /MPa | 8h loss rate |
|-----|----------------|---------------------|---------------------------|----------------|------------------|------------------|----------------|-------------------|-------------|
| 1#  | 29.00          | 903                 | 766                       | 136             | 13.5%            | 130.2            | 18.9           | 751               | 2.1%        |
|     | 26.00          | 911                 | 760                       | 150             | 14.9%            | 114.6            | 18.2           | 742               | 2.4%        |
|     | 23.00          | 904                 | 760                       | 145             | 14.4%            | 103.6            | 16.3           | 737               | 3.0%        |
| 2#  | 9.00           | 891                 | 735                       | 157             | 16.1%            | 39.6             | 6.4            | 711               | 3.2%        |
|     | 6.00           | 882                 | 733                       | 149             | 15.4%            | 26.3             | 4.3            | 701               | 4.4%        |
|     | 3.00           | 899                 | 741                       | 158             | 16.1%            | 13.4             | 2.2            | 709               | 4.3%        |
| 3#  | 9.00           | 890                 | 738                       | 151             | 17.0%            | 39.9             | 6.2            | 703               | 4.8%        |
|     | 6.00           | 884                 | 739                       | 146             | 15.4%            | 26.3             | 4.2            | 701               | 5.1%        |
|     | 3.00           | 882                 | 730                       | 152             | 17.6%            | 13.2             | 2.2            | 677               | 7.3%        |

Prestress monitoring of unbonded prestressed steel cable plan is shown in Table 3. The first prestress loss (anchorage deformation and reinforcement shrinkage) of unbonded steel strand prestressed anchor cable is 8.6% ~ 19.6%, and the first prestress loss of prestressed steel strand anchorage system is close to the theoretical calculation value of the code. The loss of prestress after anchor cable anchoring is smaller than that of anchor rod.

The research of other scholars [4, 5] also shows that the first batch of lost prestress of finish rolled rebar prestressed anchorage is larger than the theoretical calculation, and the actual loss in the vertical prestressed system of the bridge is 15% ~20%, and the loss also reaches more than 13% under the condition of long anchor length in this test. It is suggested that super-tensioning or secondary
tensioning should be adopted when the prestressed anchorage system of finish rolled rebar is adopted, and the loss of prestress should be fully considered.

### Table 3. Prestress Loss of Plan B

| No. | Free length /m | Tensile stress /MPa | Post-anchoring stress /MPa | Loss value /MPa | Loss Rate | Tension length/mm | Clamp retraction/mm | Stress after 8h /MPa | 8h loss rate |
|-----|----------------|---------------------|-----------------------------|----------------|-----------|-------------------|---------------------|---------------------|-------------|
| 4#  | 21.95          | 1141                | 1098                        | 42             | 3.7%      | 124.3             | 4.2                 | 999                 | 0.4%        |
|     | 17.95          | 1134                | 1032                        | 102            | 9.0%      | 100.1             | 4.6                 | 901                 | 0.3%        |
|     | 13.95          | 1136                | 1038                        | 98             | 8.6%      | 79.3              | 4.8                 | 888                 | 0.3%        |
| 5#  | 11.95          | 1141                | 1048                        | 92             | 8.1%      | 67.5              | 4.8                 | 901                 | 0.3%        |
|     | 7.95           | 1134                | 1013                        | 121            | 10.7%     | 44.4              | 5.0                 | 901                 | 0.3%        |
|     | 3.95           | 1136                | 934                         | 202            | 17.8%     | 22.3              | 5.2                 | 888                 | 0.3%        |
| 6#  | 9.00           | 1141                | 1018                        | 123            | 10.8%     | 50.3              | 5.0                 | 901                 | 0.3%        |
|     | 6.00           | 1134                | 961                         | 173            | 15.3%     | 33.2              | 5.0                 | 888                 | 0.3%        |
|     | 3.00           | 1136                | 913                         | 223            | 19.6%     | 16.7              | 5.1                 | 888                 | 0.3%        |

3.2. Concrete stress

Figure 2 (a) and Figure 2 (b) show the increased strain of the dam body facing the water surface after prestressing is applied. When the anchor rod is prestressed in layers, the vertical stress of dam concrete in the plan of prestressed broaching self-locking anchor rod and unbonded steel strand prestressed anchor cable increases linearly as a whole. From the strain distribution of the dam body facing the water surface, it can be seen that the two plans have achieved the effect of increasing the vertical compressive stress by applying prestress in layers. The closer Plan A and Plan B are to the end of the anchorage section and the backing plate on the top surface of the dam body, the greater the vertical compressive stress of the dam body concrete.

The results of strain test show that the additional tensile strain of 2 # and 3 # with prestressed broaching self-locking bolt appears at 4m, 4.25m, 7m and 7.25m from the ground, and the additional tensile strain of 5 # and 6 # concrete also appears at the anchorage section (4 ~ 14m).

By ABAQUS, the finite element simulation analysis of this working condition is carried out. The concrete, anchor rod, anchor head steel and grouting material adopt elastic constitutive relation, and only consider additional stress state without considering its plastic influence. The elastic modulus of concrete and grouting material is $3.0 \times 10^4MPa$, Poisson's ratio is 0.17. The steel is $2.0 \times 10^5MPa$ and Poisson's ratio is 0.2. It is assumed that there is no relative sliding between anchor head (anchor cable), grouting material and concrete.
The cloud picture of vertical distribution of 2# hole in anchor rod plan is shown in Figure 3. The maximum tensile stress occurs in the local concrete area near the first, second and third layers of anchor heads. The maximum additional tensile stress is 0.89MPa. The radius of the additional tensile stress area of the first layer of anchor heads is 1.1m and the height is 2.5m, the radius of the additional tensile stress area of the second layer of anchor heads is 0.6m and the height is 1.6m, and the radius of the additional tensile stress area of the third layer of anchor heads is 0.3m and the height is 0.6m.

The cloud picture of vertical distribution of hole 5# of anchor cable plan is shown in Figure 4. The maximum additional tensile stress is 1.54MPa, the radius of the first tensile stress zone is 2.68m and the height is 4.3m, the radius of the second tensile stress zone is 1.36m and the height is 2.3m, and the radius of the third tensile stress zone is 0.45 m and the height is 1.5m.

When the prestress load is the same, the maximum additional tensile stress of concrete in the anchor plan is about 54% smaller than that in the anchor cable plan, and the range is relatively small, so the concrete stress is more reasonable than that in the anchor cable plan.

4. Test Results

- When the broaching finish rolled threaded steel anchor rod is locked with the reinforced dam body through the pre-tightening nut, the loss rate of corresponding steel bar stress is 15.1% ~ 17.6%. The first batch of prestress loss is related to the length of the free section of the anchor rod. The shorter the length of the free section, the greater the prestress loss, but it is not nonlinear. The loss of prestress anchorage with finish rolled rebar prestress is large, and the loss of prestress should be fully considered by over-tensioning or secondary tensioning when in use.

- The first batch of prestress loss (anchoring deformation and reinforcement shrinkage) of unbonded steel strand prestressed anchor cable is 8.6% ~ 19.6%, and the first batch of prestress loss of prestressed steel strand anchoring system is close to the theoretical calculation value of the code. The loss of prestress after anchor cable anchoring is smaller than that of anchor rod.

- The effect of increasing vertical stress originally designed has been achieved by adopting broaching finish rolled threaded steel anchor rod and unbonded steel strand prestressed anchor cable. In the anchorage section, both plans have tensile areas. When the prestress load is the same, the maximum additional tensile stress of concrete in the anchor plan is about 54% smaller than that in the anchor cable plan, and the range is relatively small. The concrete stress is more reasonable than that in the anchor cable plan.

- Compared with prestressed anchor cable, the anchoring section of prestressed broaching self-locking anchor rod is shorter, making the construction more convenient and controllable. From an
economic point of view, the unit length price of broaching self-locking finish rolled threaded steel bolt is relatively high, but the anchoring length is relatively short, and the comprehensive economic effect is equivalent.

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