Structural Characteristics and Design of the New Prestressed Linings with Unbonded Annular Anchors

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Abstract. The new prestressed reinforced concrete lining with multi-layer (up to 2) multi-hoop (up to 2) un-bonded annular anchors (hereinafter referred to as MUAA lining) is a new type of structure suitable for hydraulic pressure tunnel. The structural characteristics and design concept of MUAA lining are put forward through comprehensively analysis on the structural system, annular anchor winding mode, internal force transfer process, anchorage block-out position and lining thickness. This lining produces radial precompressive stress of the concrete through the unbonded annular sealing curve anchor cable embedded in the jack tensioning lining, which makes full use of the superior tensile and imperforation performance of the prestressed concrete structure, and at the same time the surrounding rock is not required to provide all the reaction force. It can reduce load sharing of the surrounding rock by increasing the active prestress of anchors, and it is not limited by the geological conditions of surrounding rock, so it has broad engineering application value.

1. Introduction
In recent years, a large number of pressure tunnels with high internal pressure and large diameter have played important roles in major water conservancy and hydropower projects [1]. Conventional reinforced concrete lining is easy to crack under high internal water pressure. It is difficult to weld the outer side of the sheet-reinforced concrete lining structure, which often cause a lack of durability [2]. The high-pressure grouting lining requires the surrounding rock to provide all the reaction force of applying prestress, which requires more on the strength of surrounding rock and the thickness of tunnel overburden [3]. Therefore, the problems of large diameter pressure tunnel linings [4] have always been difficult to solve: poor quality of surrounding rock, thin overburden and high internal pressure, which are great challenges in the construction of water conservancy and hydropower projects [5]. The design concept of prestressed lining with curved anchors was put forward in the surge tank project of San Fiorimo Hydropower Station in Italy [6]. By applying prestressing stress to offset the tensile stress caused by the internal water pressure, the lining becomes a crack resistant structure to realize seepage prevention and bearing, and this has been successfully tested in the hydraulic projects in Italy and Switzerland [7]. In China, the structural form of such lining and the arrangement of anchors are constantly improved and perfected, and the new prestressed multi-layer multi-hoop unbonded annular anchor lining is gradually developed (Fig.1).

According to the different contact relationship between the prestressed tendons and concrete, the prestressed annular anchor lining can be divided into two types: bonded and unbonded. At present, the unbonded annular anchor lining has been successfully practiced in Switzerland's Crimsel Tailrace pressure tunnel, Italy's Presenzano surge tank, Xiaolangdi pressure silt-releasing tunnel and Dahufang water conveying tunnel. The engineering applications show that compared with the bonded
prestressed annular anchor lining structure, the MUAA lining’s advantage lies in more uniform stress on the whole lining, greatly reduced prestress loss, less steel strand material, smaller prestressed weak area of the lining and more convenient construction [9].

**Figure 1.** The new prestressed multi-layer multi-hoop unbonded annular anchor lining.

In MUAA lining, the concrete creates radial precompression stress through the unbonded annular sealing curve anchors embedded in the jacking tensioning lining, which makes full use of the superior tensile and anti-seepage function of the prestressed concrete structure, also, unlike the grouting prestressed lining, it does not need the surrounding rock to provide all the reaction force. It can reduce the load sharing of surrounding rock by increasing the active prestress of anchors and is not restricted by the geological conditions of surrounding rock.

2. Lining structure

2.1. Structural systems

In the MUAA lining, both ends of the annular anchors are anchored on the same floating anchor plate in the reserved anchorage block-out, and the annular anchor extrudes the reinforced concrete through the angle deflector and the tensioning of the jack, so that the lining can produce the annular prestress. Then, the micro-expansion concrete helps the anchorage block-out to close, so that a uniform prestressed structure system is formed in the lining. Therefore, the unbonded annular anchor and the anchoring system are the source of the prestressing of the lining, the tension is the energy source, the reinforced concrete of the lining is the carrier to realize the prestressing of the structure, and the anticorrosion system is the long-term and effective guarantee of the lining [10].

In view of this, the structural systems of MUAA lining can be divided into anchoring system, annular anchor tensioning system, lining reinforced concrete system, and annular anchor anticorrosion system.

2.2. Anchoring system

The unbonded prestressed annular anchor system is mainly composed of unbonded annular anchor, operation anchor plate, operation clip, sealing plate, steel splint and screws. The schematic diagram of unbonded prestressed annular anchor anchoring principle is shown in Fig.2.

The operation anchor plate is the core force unit of the tensioned anchoring in the entire annular prestressed system, in actual construction, a travelling anchor plate with anchoring end and tensioning end is adopted, where the anchor hole of the tensioning end is designed in the middle, and the anchor hole of the anchoring end is set on both sides of the anchor plate, which realizes a compact appearance of the anchor plate and uniform prestressing distribution. The annular anchor operation clip is a key part of the anchoring system, which requires high quality alloy steel, and the processing and heating treatment must be strictly controlled. There are taper holes on the working anchor plate, which cooperate with the clip, and the anchors is anchored by the wedge tightening principle of taper holes.
The operation anchor plate and the working clip of the unbonded prestressed anchoring system are subjected to long-term load, so it is particularly critical to ensure the effectiveness of the anchoring.

Figure 2. Schematic diagram of anchoring principle of unbonded annular anchor.

2.3. Tensioning system
Reasonable, quick and accurate annular anchor tensioning is an important guarantee for the construction quality of prestressed annular anchor, and the selection of annular anchor tensioning equipment is very important. The annular anchor tensioning system is mainly composed of limit plate, deflector, extension barrel, centre hole jack, oil pump and oil gauge (see Fig.3a). Fig.3b is a working drawing of the unbonded prestressed annular anchor tensioning system on site.

The annular anchor can only be tensioned at varying angles by the deflector. The friction loss of prestress is closely related to the deflector. The deflector used in the field test is a steel structure optimized from multi-section combination to two-section bend type, which not only is easy to disassemble and assemble, but also greatly reduces the friction loss rate.

The centre core jack is the executive element used with the prestressed anchor, and the oil pump is the power source adapted to the type of the jack. The on-site tensioning should be based on the principle of "light product and easy construction".

Figure 3. Working drawing of unbonded prestressed annular anchor tensioning system.

3. Mechanical characteristics of the structure
The mechanical characteristics of MUAA lining are closely related to the load transfer mode of the inner annular anchor [11]. Conventional anchors cause compressive stress in the concrete by making use of the compression from the anchoring end and the tensioning end, while the unbonded prestressed annular anchor uses the travelling anchor head which combines the anchoring end and the tensioning end to seal up the curved anchors, by means of "hoop effect", the annular tension of anchors is transformed into the radial load acting on the interface between anchors and lining, so as to produce precompression stress of concrete. As shown in Fig.4.
When the lining is prestressed, it can bear the load of internal water, so as to realize anti-crack and anti-seepage. Moreover, this kind of active prestressed structure, unlike grouted prestressed lining, does not need the surrounding rock to provide reaction force, and can greatly reduce the proportion and action of surrounding rock in load sharing.

![Diagram](image)

**Figure 4.** Schematic diagram of unbonded annular anchors load in MUAA lining.

Take double-loop winding annular anchor as an example, the action mode of annular tension load inside the lining is shown in Fig. 4, and the annular tension load will tighten the lining at the interface between lining concrete and annular anchor and be transformed into radial equivalent load.

The force transmission characteristics of the prestressed annular anchor and the lining concrete are abstracted into the annular anchor lining differential element as shown in Fig.4b. The tensile forces at each end of the annular anchor are respectively \( T \) and \( T + dT \); the longitudinal loading width is \( B \); it is assumed that the concrete stress distribution on the differential element is uniform; the equivalent load of normal prestress is \( P_v \); the center angle of the differential element is \( d\theta \); \( F \) is the tensile force at one end of the annular anchor; \( F' \) is the tensile force at the other end. According to the normal mechanical equilibrium condition, it can be obtained:

\[
(2T + dT) \cdot \sin \left( \frac{d\theta}{2} \right) - r \cdot d\theta \cdot B \cdot P_v = 0
\]

(1)

For unbonded annular anchor lining, polyethylene case will be set between the annular anchor and concrete and filled with grease. The friction coefficient of the contact surface is generally less than 0.03. In order to simplify the calculation, the friction force can be ignored \((F=0)\). If \( d\theta \) is small enough, it is advisable to expand \( \sin \left( \frac{d\theta}{2} \right) \) according to Taylor series and omit high-order trace, so \( \sin \left( \frac{d\theta}{2} \right) = \frac{d\theta}{2} \). Then, by simplifying Equation (1), the equivalent prestress load of annular anchor lining can be expressed as:

\[
P_v = \frac{T}{r \cdot B}
\]

(2)

**4. Joint bearing effect of surrounding rock and MUAA lining**

For prestressed anchor annular lining structure system of pressure tunnels, under the combined action of prestress, internal water pressure, external water pressure, dead weight stress and surrounding rock pressure, the joint bearing characteristics of surrounding rock and lining are more complex, and the interaction between surrounding rock and lining will change in different stages of construction period, operation period and maintenance period.

During the construction period, the surrounding rock is unloaded. After the MUAA lining is applied, the lining and the surrounding rock are squeezed together to bear the pressure of the surrounding rock. As the prestress is applied, annular anchor is rapidly tensioned by the jack, the lining inside shrink,
and the upper part of the lining and surrounding rock release gradually, with the increase of tension, the gap opening between the surrounding rock and the lining gradually increases, and then, only the lower half of the lining is in contact with the surrounding rock, and the lining only bears self-weight stress, the annular anchor prestress and the supporting force of the lower surrounding rock, and no longer bears the load; with the backfilling and grouting behind the lining, the surrounding rock wraps the lining, and the two closely fit together to bear the load. Then, the contact pressure will gradually increase with the release of the surrounding rock stress.

During the operation period, the prestressed annular anchor lining does not crack under internal water load in principle. Unlike limit design lining crack, the annular anchor lining will not be separated from the surrounding rock due to the excessive seepage force of the internal and external water heads. Under the combined action of various pressures, the surrounding rock and the lining will squeeze and jointly bear the load. The load sharing between the two is related to the strength of the surrounding rock and the lining. When the prestress of the lining is sufficient, the load shared by the surrounding rock is very small.

In the in-situ test, when the prestressed MUAA lining was under an internal water load, the contact pressure curve for the surrounding rock and lining was measured; it is shown in Fig.5. It can be seen that the contact stress gradually increases along with the increase in the load level. The internal water load is transferred from the inner side of the lining to the surface of the surrounding rock and deeper. The results of the spatial distribution of the contact pressure between the surrounding rock and the MUAA lining (Fig.5) show that the contact pressure at the crown is much smaller than that at the inverted arch and that the maximum contact stress of 15.59 kPa appears near the inverted arch of the tunnel.

![Figure 5. Contact pressure and Spatial distribution of the measured contact stress.](image)

The measurement results of the joint meter (Fig.6) indicate that the MUAA lining has shrunk owing to the tension of the annular anchors before the internal water pressure is applied, therefore, the middle and upper parts of the lining will be separated from the surrounding rock.

![Figure 6. Change of crevice between the surrounding rock and MUAA lining.](image)

During the maintenance period, with the dissipation of the internal water pressure, the prestressed lining shrinks again. The surrounding rock previously in the plastic state has residual deformation, and
there will be a small gap between the lining and the surrounding rock after unloading, and the two are partially detached. The lining is mainly affected by prestress, external water pressure and dead weight stress, while the surrounding rock mainly needs to bear the pressure of itself.

5. Conclusions
In the MUAA lining, the curved anchors are sealed by the travelling anchor head combining the anchoring end and the tensioning end, and the annular tension of the anchors is transformed into the radial load acting on the interface between the anchors and the lining through "hoop effect", so that the precompressive stress of the concrete can be generated. Reasonable winding mode of annular anchors and location of anchor block-outs play an important role in improving prestress. The loading capacity can be increased or decreased by adjusting the thickness of lining and the annular anchor spacing. Circular cross-section is more efficient in prestressing than horseshoe cross-section lining.

6. References
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Acknowledgments
The work presented in this paper was financially supported by National Key R&D Project of China (Grant No. 2017YFC1501100), the National Natural Science Foundation of China (Grant No. 52079150) and Natural Science Foundation of Shaanxi Province (Grant No. 2019JLZ-13, Grant No. 2019JLP-23, Grant No. 2019JLP-26).