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Innovative loading system for applying internal pressure to a test model of pre-stressed concrete lining in pressure tunnels

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ABSTRACT

Pre-stressed concrete linings are often used in tunnels subjected to internal water pressure. Test models are important for the better understanding of their performance. We present an innovative loading system to apply internal pressure on such linings. The loading system consists of circular flat jacks inside the pre-stressed concrete lining. The circular flat jacks are cushions of steel membrane. Uniform pressure can be generated by inflating the steel cushions against the pre-stressed concrete lining and an inner concrete lining. The inner concrete lining serves as a reaction buttress. The design principles and manufacture details of this system are discussed in this paper. And its performance is demonstrated by some test results.

Keywords: pre-stressed concrete lining, pressure tunnel, model test, circular flat jack.

INTRODUCTION

Large hydropower projects are often characterized by high dams and deep caverns, which give rise to large pressure tunnels with high internal water pressure (Pachoud, A. J. et al., 2016; Lu, A. Z. et al., 2011). The low tensile strength of concrete combined with high internal pressure means that tunnel linings of plain concrete and reinforced concrete are prone to crack formation, which may undermine their serviceability (Sari Y. D. et al., 2008; Taras A. et al., 2007; Vengosh A. et al., 2014; Yang X. L. et al., 2013). Inspired by the pre-stressing technique in structural engineering, pre-stressed tunnel lining was used for the first time in hydropower project in Austria in the 1960s (Matt P. et al., 1978). A compressive stress was generated by grouting before the lining was put in service. The tensile stress induced by the internal water pressure was largely reduced by the compressive stress, so that lining with plain concrete or with concrete of low reinforcement could be carried out (Ravkin A. A. et al., 1989). Obviously, the pre-stress by grouting relies on the ground reaction force (Heger F. J.et al., 1990; Seo H. J. et al., 2015), which is sufficiently available for pressure tunnels in sound ground and with thick overburden. For pressure tunnels in poor ground and with thin overburden, however, the lining design remains a challenging issue. It was not until 1973 when anchored circular tendons were used in the pre-stressed linings at San Fiorino in Italy (Matt P. et al., 1978). It is one kind of lining form, in which pre-stressed anchor rope is wrapped around the lining for one or two circles and its two ends are fixed in one same anchorage to apply pre-compressive stress. Till now, this kind of structure form has been used in several hydraulic tunnel projects all round the world. From the perspective of real application, there inevitably exists a defect in some built projects, because of lacking mature designing theory and guidance specification, which increased construction risk and impeded the popularization of this technique. When the designing theory of circular anchor pre-stressed concrete lining is still unknown, model or in-situ test is the best method to solve engineering design problems. And the test is further divided into tension test and inner water pressure test. The tension test improves the construction technology, while the inner water pressure test explores the lining's operation situation during the running period. By combining the two tests, the rationality of the parameters used in the circular anchor pre-stressed lining's design can be guaranteed; and the safety of the project can be approved, both for construction and running. The present material shows that, in most built circular anchor pre-stressed lining projects, only process test at construction stage has been conducted by model or in-situ experiments (Lin X. S. et al., 1999; Kang J. F. et al., 2003). Thus, there lacks research about the operation situation of tunnels under inner water pressure at running stage. And also, existing inner water pressure loading methods have certain limitations.

Literature Review

The circular anchor pre-stress lining is first successfully used in the surge tank project in Italy's San Fiorino hydropower Station in 1973 (Matt P. et al., 1978). Compared with pre-stressed lining by grouting, the compressive stress in the lining is balanced by the tensile force in the tendons and does not require the ground reaction force (Matt P. et al., 1978; Kang J. F. et al., 2014; Wang X. Z. et al., 2014). The circular tendons can be installed either bonded or un-bonded. Such linings were widely used in many parts of the world (Trucco G. et al., 1978; Kazuyoshi et al., 2003; Nagamoto et al., 2008; Wang X. Z. et al., 2013). However, the lining design, for example, the lining-thickness, the number of and the spacing between the tendons, and the tensile force, is mainly based on experience in similar geological setting (Sui C. E. et al., 2014). In order to better understand the performance and to optimize the design of pre-stressed linings, in-situ measurements of pre-stressed linings in service state are needed.

Unfortunately, well documented in-situ measurements are expensive and rare. The model test under well-defined boundary conditions offers an attractive alternative. The quality of model tests is mainly decided by the loading system for internal pressure. Till now, there are only few researches about circular anchor concrete lining with internal water pressure. There are mainly two kinds of loading systems in practice, that is, servo-controlled hydraulic jacks and water pressure (Lin X. S. et al., 1999; Kang J. F. et al., 2003). In the first loading system, the internal pressure is applied by a number of symmetrically arranged hydraulic jacks. For example, 12 hydraulic jacks were used in the model tests at Xiaolangdi in China (see Figure 1(b) and Figure 1(c)); the photo of the model is also shown in Figure 1(a). For easier loading, the simulation model used in Xiaolangdi is designed as a circular tunnel with an upward opening. In the tunnel, by laying bricks with a certain thickness, the supports reach the predetermined loading height position. Each jack corresponds to a support block, and the support block is a concrete specimen. The jack pressure is loaded step by step by oil pump until the force is finally loaded onto the lining through support block (Lin X. S. et al., 1999). In the second loading system, the internal pressure is applied by water pump. A lining segment is blocked, and water proofed at both ends leaving an inlet and outlet vent for water ingress and air exit (see Figure 1(a) and Figure 1(d)) (Kang J. F. et al., 2003). After the model ends are sealed, water is injected by high pressure pump, and the inner pressure level can be monitored by pressure gauge, in order to simulate the inner water pressure load.

The first loading system has the advantage of being simple and robust. The disadvantage lies in the fact that the internal loads are applied at individual points and may differ from the uniform water pressure. Moreover, the test results are very sensitive to the position and synchronization of the jacks. The second loading system has the advantage that the pressure is uniform. However, the loading system is rather prone to leakage at high water pressure. For example, the model test at Xiaolangdi was stopped at the pressure of about 1.4MPa due to leakage (Lin X. S. et al., 1999). The second loading system has more difficulties when used in in-situ water injection test. First, the water transportation and continuous supply is hard to be guaranteed. Second, because the tunnel is sealed, its two water plugging ends are segregated. So the problem of communication and water leakage is hard to be solved. Lastly, the water drainage after the test will cause serious damage to the surrounding construction environment. Thus, it is necessary to develop a new open enthronement-friendly internal water pressure loading system, which is of great importance to the test of pre-stress effect and the improvement of the construction technology of pre-stress circular anchor.

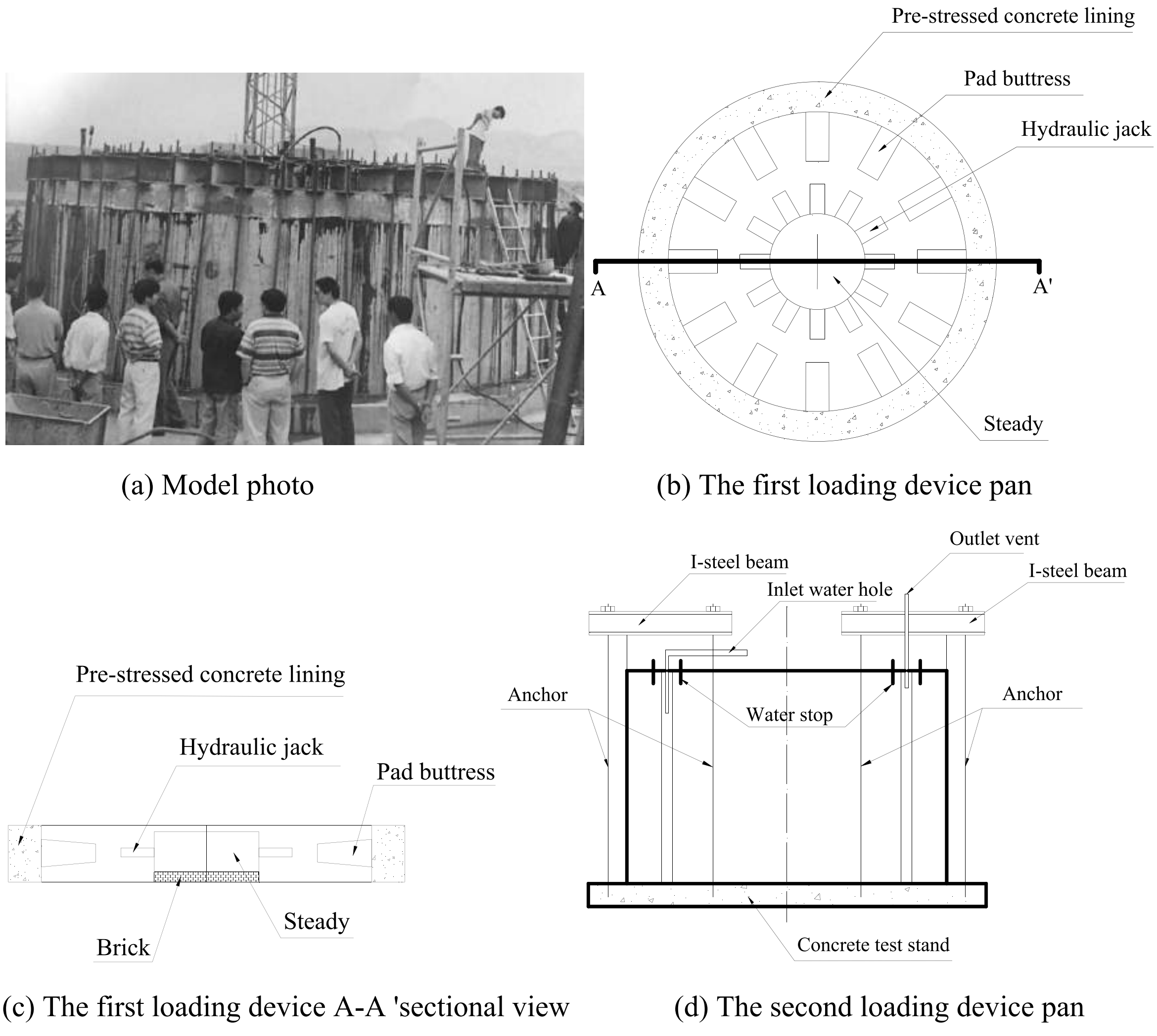


Figure 1. Schematic of Xiaolangdi model test loading device.

DESIGN OF LOADING SYSTEM

The loading system

As stated above, it is desirable to develop a new loading system, which is simple, robust and with uniform pressure. We proceed to describe the design principle of such a system. Our loading system consists of circular flat jacks placed between the pre-stressed concrete lining and an internal reaction concrete lining (see Figure 2). A circular flat jack consists of several arc flat jacks. Several arc flat jacks are connected by threaded steel pipes to form a circular flat jack along the lining. An arc flat jack is curved cushions of welded steel membranes, which can be inflated with a hydraulic pump. The circular flat jack has a water hole at the bottom of the tunnel and a vent at the top. The water hole is connected with a hydraulic pump. And two water pressure gauges are installed at both the bottom water intake and the top vent. The air outlet and water injection hole are made by threaded steel pipe with an outer diameter of 18~32mm. Obviously, the radius of the arc should be the inner radius of the pre-stressed concrete lining. The thickness of the arc flat jacks, the arc length, and the width of the arc flat jacks will be discussed later. The pre-stressed concrete lining is a circular anchor pressure liner, in which the pre-stressed anchor rope is wrapped around the lining for one circle or two circles, and its two ends are fixed in one same anchorage to apply pre-compressive stress. Reaction concrete lining is plain concrete liner that needs no reinforcement because circular flat jacks apply only compressive force onto it. The concrete grade and thickness can be the same with pre-stressed concrete lining. This loading system is robust and easy to use that it can be used for model tests in laboratory as well as for full scale test in-situ.

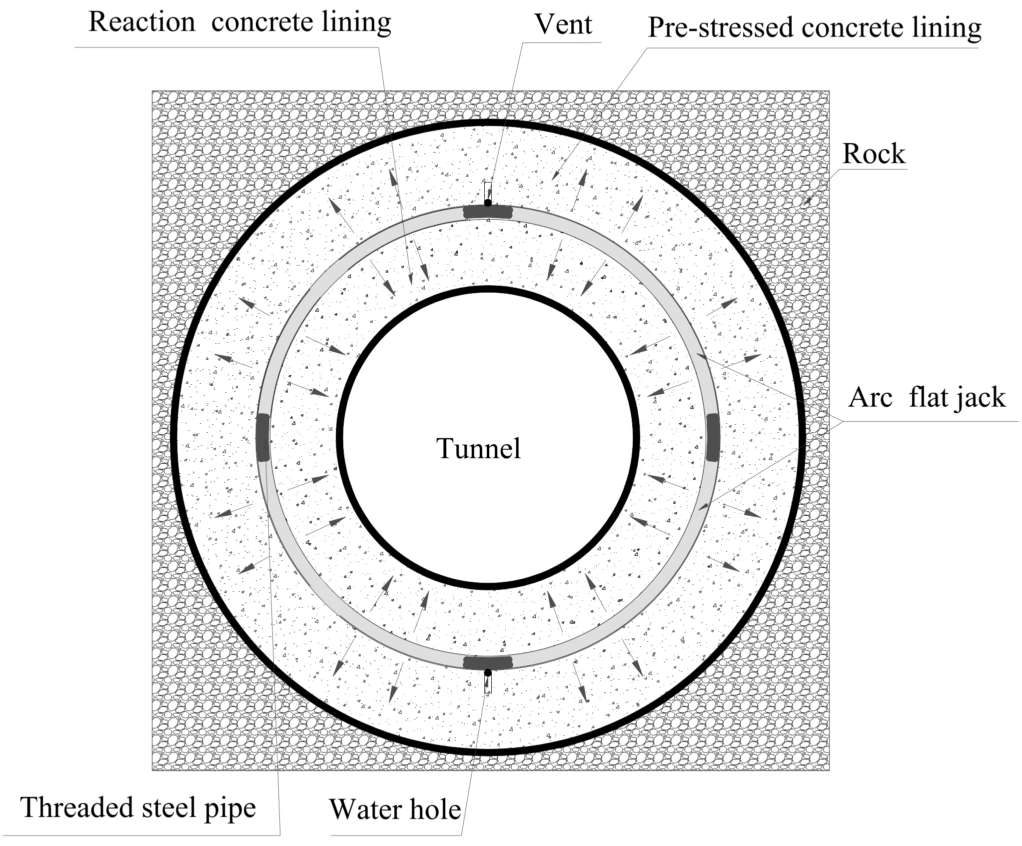


Figure 2. Design of loading system.

The method of building up the system and test procedure is as follows. First, the inner and outer layers of steel bars of the pre-stressed lining are assembled; then the pouring template is built and concrete poured. After 28 days with other construction procedures completed, the arc flat jacks are installed on the pre-stressed concrete lining with expansion bolts at the fixed position (see Fig. 3.). The arc flat jacks are connected with each other by threaded steel pipes. When the circular flat jacks are installed, they are then inflated with a hydraulic pump to detect any leakage or damage. Afterwards, the reaction concrete lining is cast in place against the circular flat jacks with a circular shattering. Pre-stressed concrete lining and reaction concrete lining can be poured by special circular tunnel concrete placing trolley and also can be poured by integrating a template assembled using small steel form-works. The test can be started some 28 days after the reaction concrete lining is installed. The test is carried out by increasing the pressure in the circular flat jacks with the hydraulic pump and measuring the displacements. In order to check the effect of internal water pressure loading, strain gauge is embedded in pre-stressed lining to monitor the force conditions of its different areas. Surface strain gauge or other monitors put on the inner surface of reaction concrete lining can also be used to survey the force evenness of the lining.

Design of circular flat jack

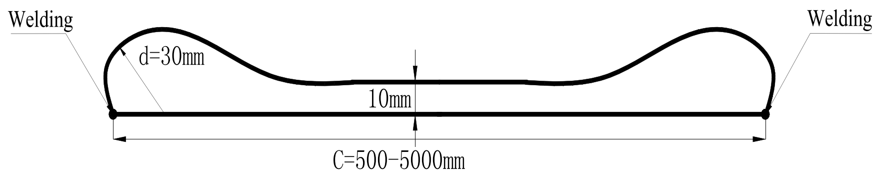
We choose to use steel sheet (plate) with a thickness of 1 mm. Steel sheets of this thickness possess sufficient strength to withstand high pressure and offer the required flexibility to work with. The length of an arc flat jack can be chosen between 500 mm and 5000 mm depending on the inner radius of the pre-stressed concrete lining. And the width of an arc flat jack can be chosen between 200 mm and 1000 mm depending on the pre-stressed concrete lining width. Figure 3 shows the cross section through an arc flat jack. The arc flat jack consists of a flat bottom steel plate and a slightly larger top plate, which are welded together to form a cushion. In a natural state (not inflated), the arc flat jack has a thickness of about 10 mm in the center and about 30 mm at the edges. Several arc flat jacks are connected by threaded steel pipes to form a circular flat jack (see Fig. 4.). When inflated, the circular flat jacks will have radial deformation to exert pressure onto the pre-stressed concrete lining and reaction concrete lining directly in order to realize the simulation of inner water pressure.

When designing the circular flat jack's system, its parameters are decided by the internal diameter and the loading width of the pre-stressed lining. The method to decide the parameters is as follows. Assume that the internal diameter of the pre-stressed lining is D; the width of an arc flat jack is B and the length is C (as shown in Figure 3(b)); the gap between each arc flat jack along the hoop direction is H, and then the length of the threaded steel pipe is H; the gap between the circular flat jacks along the axis direction is L (as shown in Figure 4(b)). One circular flat jack consists of m arc flat jacks, and one circular flat jacks loading system consists of n circular flat jacks. Then, there are the following formulas:

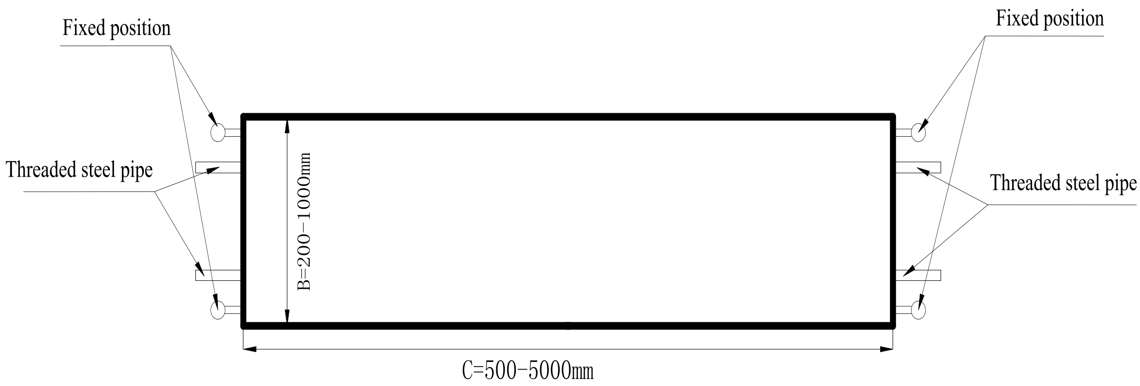
$$W = nB + (n-1)L \quad (1)$$

$$\pi D = m(C+H) \quad (2)$$

According to engineering practice, D and W are known; and B ranges from 200mm to 1000mm; H ranges from 50mm to 300mm. L can be calculated through formula (1) by selecting a proper B value and the number of circular flat jacks n, in line with the W value. According to D, the circumference of the circular flat jacks can be derived and by selecting the proper H value and the number of arc flat jacks m, the length of a singular arc flat jack C can be derived from formula (2). After the parameters of the arc flat jack are determined, the arc flat jacks are manufactured at the factory and installed on site after acceptance. The circular flat jack has a water hole at the bottom of the tunnel and a vent at the top. Before being pressed, water is filled in through the threaded steel pipes in order to empty the air in circular flat jacks. And then, more water is filled in to create the required pressure. As an independent closed system, the circular flat jacks could use water pressure to generate radial deformation in order to apply pressure onto the reaction concrete lining and pre-stressed concrete lining at the same time.



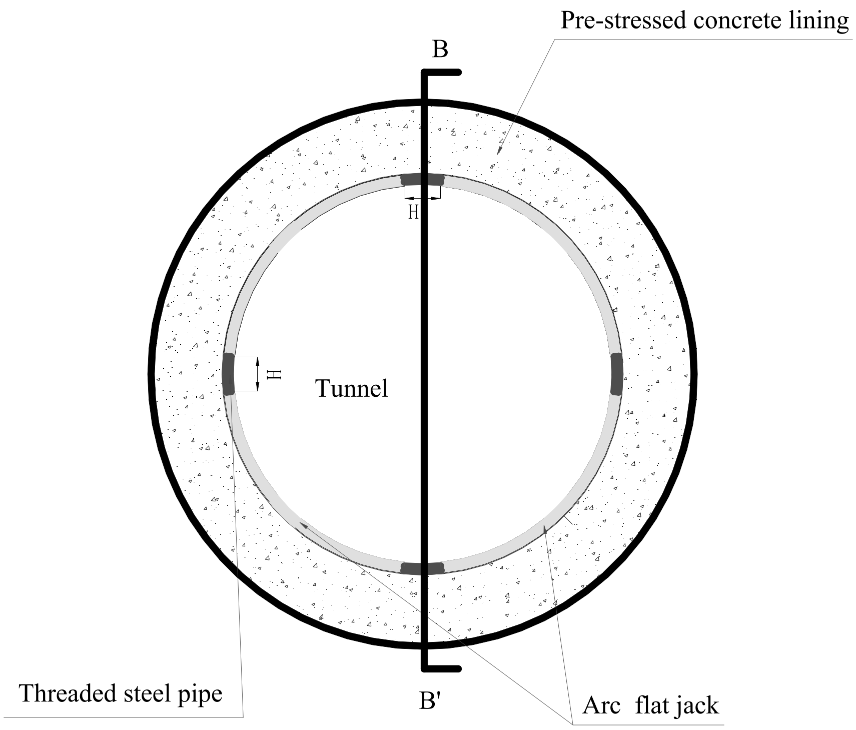
（a）Longitudinal diagram of an arc flat jack



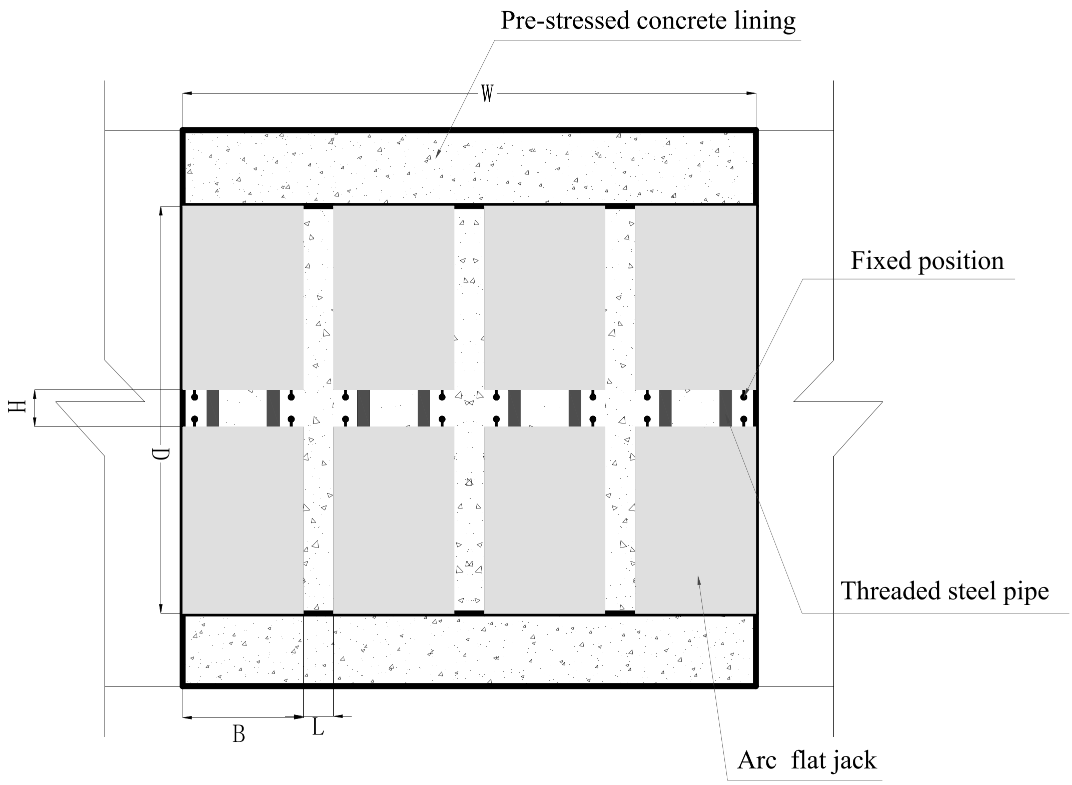
（b）Horizontal diagram of an arc flat jack

Figure 3. Cross section through an arc flat jack.

The main function of circular flat jack is to adapt to pre-stressed concrete lining and reaction concrete lining's deformation requirements and simulate the internal water pressure using the pressure caused by its water filling deformation. The thin wall of arc flat jack does not provide hoop tensile stress, so the internal water filling pressure is exerted entirely onto the pre-stressed concrete lining and reaction concrete lining, and the arc flat jack only plays a role of conductance. The main deformations of circular flat jacks are produced during water injection process. Because of the



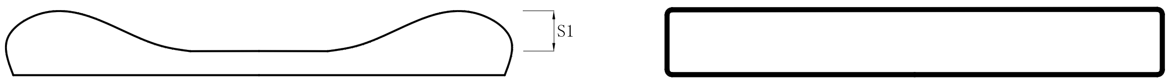
(a) Ring direction view



(b) Axially arranged the B-B' sectional view

Figure 4. Installation design schematic of circular flat jacks.

water pressure during injection, the pre-stressed concrete lining and reaction concrete lining could be regarded as two separate bodies that deform in two different radial directions both inside and outside (Fig. 2). The outer wall of circular flat jack deforms outwardly with pre-stressed concrete lining, while the inner wall deforms inwardly with reaction concrete lining. In order to avoid destruction of circular flat jack's thin steel sheet caused by greater tensile stress during deformation process, circular flat jack must be given an adequate margin of deformation to meet the reaction concrete lining and pre-stressed concrete lining's deformation correspondingly. Deformation margin can be divided into radial deformation margin and circumferential deformation margin. The deformation diagrams of arc flat jack before and after water filling are shown in Fig. 5.



(a) Before the water filling (b) After the water filling

Figure 5. The deformation of arc flat jack before and after water filling.

Fig. 5 shows that elastic deformation arc segments are set at both ends of the arc flat jack, so their thickness deformation may be significant, while the axial one is relatively minor after water filling. The purpose of setting the arc segment is to ensure that there is enough margin deformation at the section height direction (radial). Assuming that when water pressure applies to the pre-stressed concrete lining, the surrounding rock is unstressed, then radial deformation margin is only related to pre-stressed concrete lining deformation and reaction concrete lining deformation, and the minimum radial deformation margin of unilateral arc segment has to be larger than the total deformation of pre-stressed concrete lining and reaction concrete lining; that is,

$$s_1 \geq u_1 + u_2 \tag{3}$$

where s_1 is the radial deformation margin of an arc flat jack, that is, the arc segment shown in Fig. 5;

u_1 is the radial displacement of pre-stressed concrete lining;

u_2 is the radial displacement of reaction concrete lining;

From the geometric point of view, the circumferential deformation margin s_2 needs to be larger than the circumferential deformation of pre-stressed concrete lining.

$$s_2 \geq 2\pi u_1 \tag{4}$$

where s_2 is the circumferential deformation margin of a circular flat jack;

u_1 is the radial displacement of pre-stressed concrete lining.

Based on elastic mechanics, the displacement of Lame solution could be solved when thick-walled cylinder is under uniform internal and external water pressure.

$$u_r = u_\theta = \frac{1}{E}\left[-(1+\mu)\frac{a^2b^2(p_2-p_1)}{b^2-a^2}\frac{1}{\mathrm{r}} + (1-\mu)\frac{a^2p_1-b^2p_2}{b^2-a^2}\mathrm{r}\right] \tag{5}$$

where a is the inner radius of thick-walled cylinder, b is the outer radius of thick-walled cylinder;

p_1 is the internal water pressure; p2 is the external water pressure;

E is the elastic modulus of thick-walled cylinder;

μ is the Poisson's ratio of thick-walled cylinder;

u_r is the radial displacement of thick-walled cylinder; u_θ is the circumferential displacement of thick-walled cylinder.

For pre-stressed concrete lining, the circular flat jack only applies the internal water pressure onto it, while, for the reaction concrete lining, the circular flat jack only applies the external water pressure onto it. Because the circular flat jack thickness is negligible compared to the pre-stressed concrete lining radius, the calculation takes the inner radius of pre-stressed concrete lining and the outer radius of reaction concrete lining as R_2, the inner radius of reaction concrete lining as R_1, and outer radius of pre-stressed concrete lining as R_3, and p_1 equals p_2, as shown in Fig. 6.

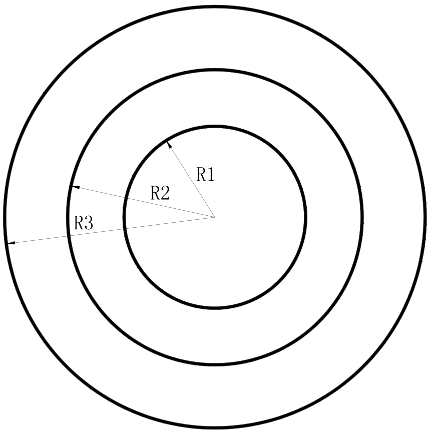


Figure 6. Tunnel computing schematic.

Since the concrete material for pre-stressed concrete lining and reaction concrete lining is the same, the elastic modulus and Poisson's ratio of both are considered equal. Based on formulae (3), (4), and (5), the radial deformation margin and circumferential deformation margin of circular flat jack can be calculated as

$$s_1 \geq \frac{R_2 p_1(1+\mu)}{E}\left(\frac{R_3^2}{R_3^2-R_2^2}+\frac{R_1^2}{R_2^2-R_1^2}\right)+\frac{R_2^3 p_1(1-\mu)}{E}\left(\frac{1}{R_3^2-R_2^2}+\frac{1}{R_2^2-R_1^2}\right) \tag{6}$$

$$s_2 \geq \frac{2\pi R_2^2 p_1}{E\left(R_3^2-R_2^2\right)}\left[\frac{R_3^2(1+\mu)}{R_2}+(1-\mu)R_2\right] \tag{7}$$

Based on the formulae (6), (7), we could know that radial and circumferential deformation margins are both the inverse functions of the elastic modulus, so the stronger the concrete, the smaller the deformation margin. Taking the pre-stressed concrete lining of Xiaolangdi desilting tunnel as an example, the outer diameter of lining is 7.8m, the inner diameter of lining is 6.5m, and the water pressure of design is 1.2MPa.

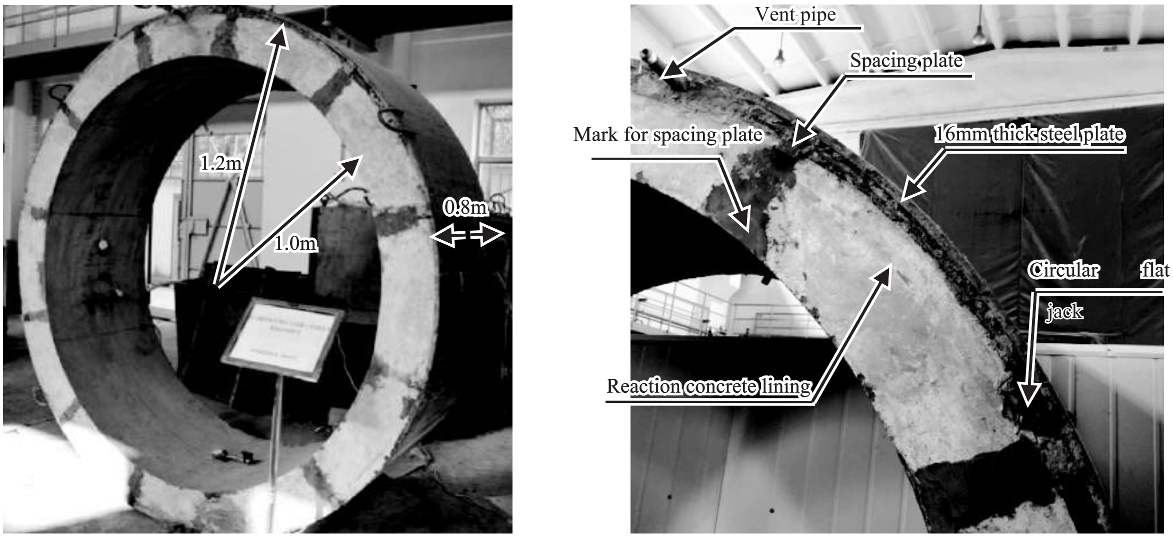
Assuming that the inner diameter of reaction concrete lining is 5.5m, both reaction concrete lining and pre-stressed concrete lining are made of C40 concrete, elastic modulus E = 32GPa, Poisson's ratio $\mu = 0.167$, the deformation of reaction concrete lining, and pre-stressed concrete lining, and the minimum radial and circumferential deformation margin of circular flat jacks are, respectively, calculated with the results shown in Table 1. Table 1 shows that because both reaction concrete lining and pre-stressed concrete lining are made of C40 high-strength concrete, the minimum radial deformation margin is only 1.42mm, and the hoop one is only 4.37mm. Therefore, the design according to Fig. 3 provides a radial margin of 20mm, which could meet the test requirement.

Table 1. Minimum residual design of flat jack in Xiaolangdi pre-stressed concrete lining (mm).

Radial of pre-stressed concrete lining	Radial of reaction concrete lining	Radial of circular flat jack	Hoop of circular flat jack
0.70	0.72	1.42	4.37

TEST MODEL AND ANALYSIS

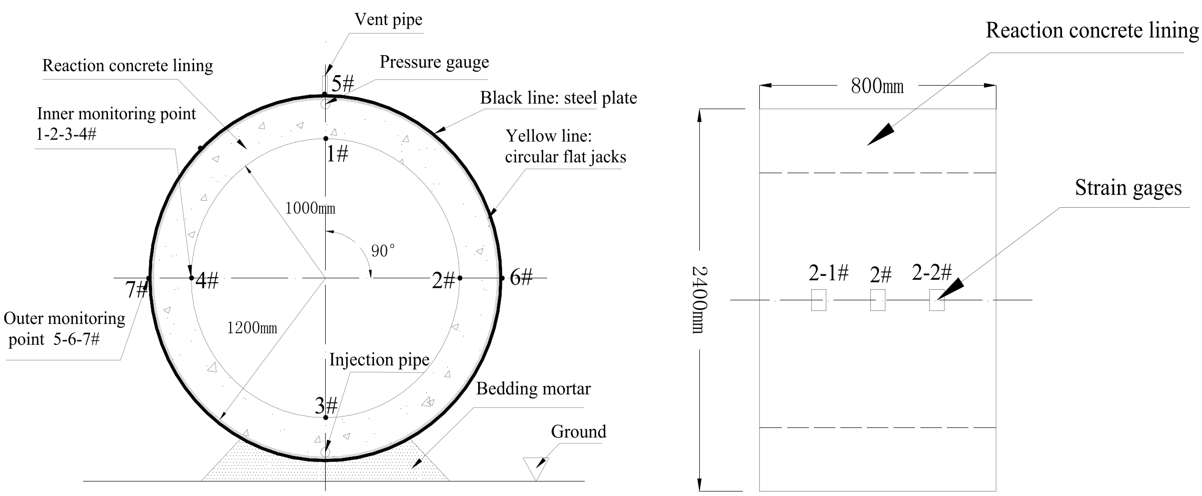
In order to prove the feasibility and effectiveness of the loading system, a cavern model segment is manufactured to simulate the water pressure loading test. The test includes the design, production, and installation of circular flat jack and the effect of the applied force. To save time and testing costs, the exterior layer pre-stressed concrete lining is replaced by a 16mm thick steel plate, and the reaction concrete lining has an inner diameter of 2.0m, thickness of 0.2m, and axial width of 0.8m. See Fig. 7 for the photo of the physical model. As for one arc flat jack, its width is 0.4m and length is 1.84m. When the maximum water injection pressure is 1.6MPa, the radial and circumferential deformation margins can be calculated according to equations (3) and (4). Due to the pre-stressed concrete lining replaced by the steel plate, in equation (3) is calculated based on thin-walled cylinder theory. The minimum radial deformation margin of the circular flat jack in the model test is calculated as 0.99mm, and the minimum circumferential deformation margin is 4.52mm. When the arc flat jack in the model test was designed as shown in Figure 3, both radial and circumferential deformation margins can meet the test deformation requirements. The circular flat jack is composed of four arc flat jacks, and every two of them are connected by a 5cm long threaded steel pipe. Axially, there are two rows of circular flat jacks that are closely placed with no pitch. Before pouring the reaction concrete lining, two rows of 0.4m wide circular flat jacks are bolted in the middle of the steel template by welding the fixed position. In order to prevent the deformation of circular flat jacks on both sides of its free surfaces, 12 spacing plates are welded on both sides of the model along its circumference, as shown in Figure 7. The elastic modulus of steel plate is 200G Pa, and the concrete of reaction concrete lining is two graded aggregates, using ordinary portland 42.5 cement with a strength grade of C40. The measured compressive strength is 42.0MPa, and the tension strength of concrete is 4.65 MPa, with $E = 38.0$G Pa and $\mu = 0.169$.



(a) The entire model (b) Local Model

Figure 7. Test model photos.

There is one monitoring section in the model to monitor the circumferential deformations, that is, the section of the centerline. Four monitoring points are, respectively, set at 0 °, 90 °, 180 °, and 270 ° positions on the inner surface of the reaction concrete lining, with one concrete strain gage set at each of the monitoring points. Measuring points are numbered 1#, 2#, 3#, and 4#. Three monitoring points are set at 0 °, 90 °, and 270 ° positions on the outer surface of the steel plate. A metal strain gage is set at each measuring point. Correspondingly, the measuring points are numbered 5#, 6#, and 7#. There is also one section to monitor the uniformity of the strain on the axial direction as shown in Fig. 8(b). Two concrete strain gauges numbered #21- and #22- are placed near point 2# along the axial direction spaced about 20cm.

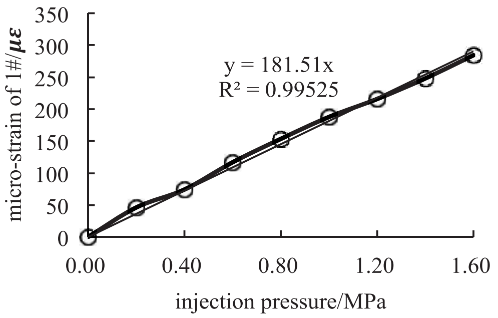


(a) Hoop measuring point (b) Longitudinal section measuring points

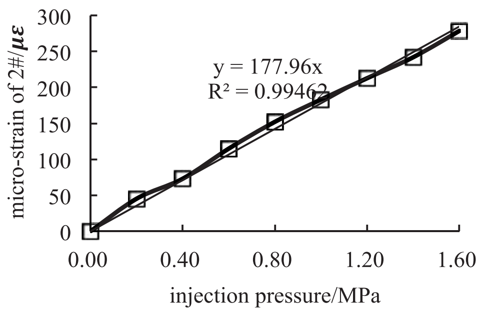
Figure 8. Model test monitoring points layout.

At the beginning of the loading test, the circular flat jacks were filled with water and the internal air was emptied. The injection pressure was added to 0.2MPa; after three times of pressurization and pressure relief, there was no water leakage appearing in any arc flat jacks connection. The pressure was increased progressively with 0.2MPa increase at each time until it reached the maximum of 1.6MPa. Then maintain that pressure for 3 minutes, and read the strain value at each point under that pressure. No leakage or pressure losing was detected in the test.

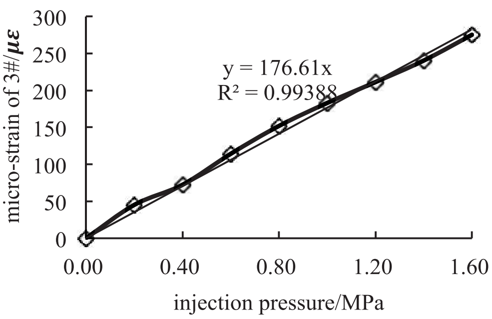
Fig. 9 shows the hoop deformation curve of the monitoring points on the inside surface of reaction concrete lining under different levels of loading pressure. Fig. 10 shows the hoop deformation curve of the monitoring points on the outside surface of steel plate under different levels of loading pressure. The axial hoop strain curve of the inside surface of reaction concrete lining is shown in Fig. 11.



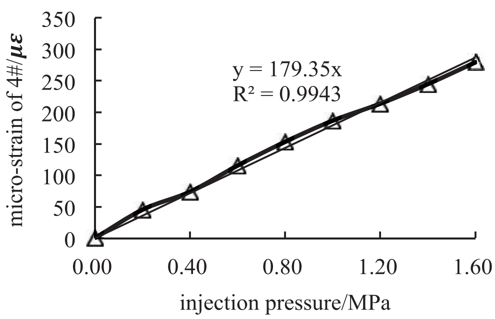
(a) 1# measuring point



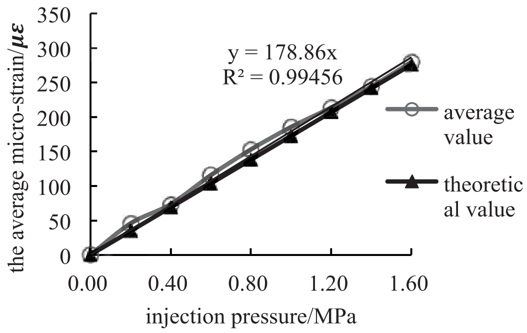
(b) 2# measuring point



(c) 3# measuring point

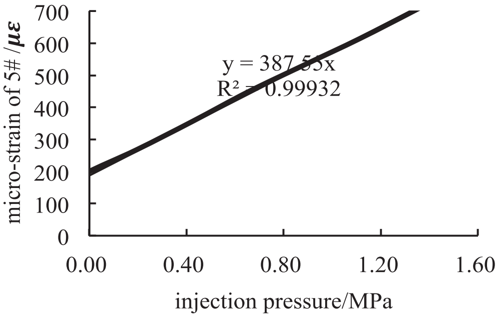


(d) 4# measuring point

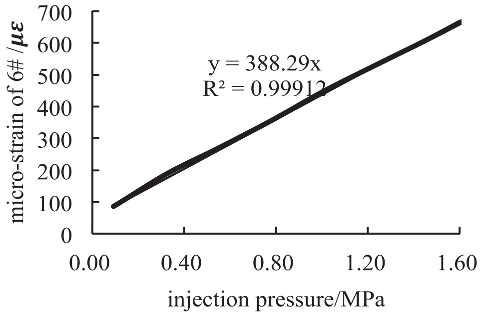


(e) Average value

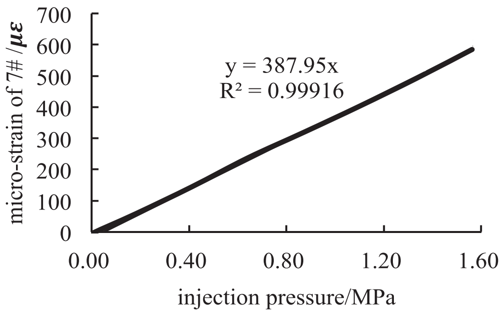
Figure 9. Hoop strain of the reaction concrete lining under the injection pressure.



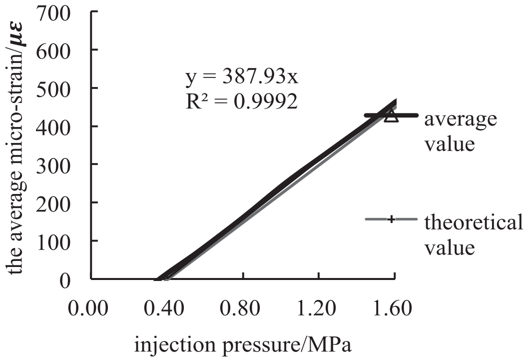
(a) 5# measuring point



(b) 6# measuring point



(c)7# measuring point



(d) Average value

Figure 10. Hoop tensile strain of steel plate under the injection pressure.

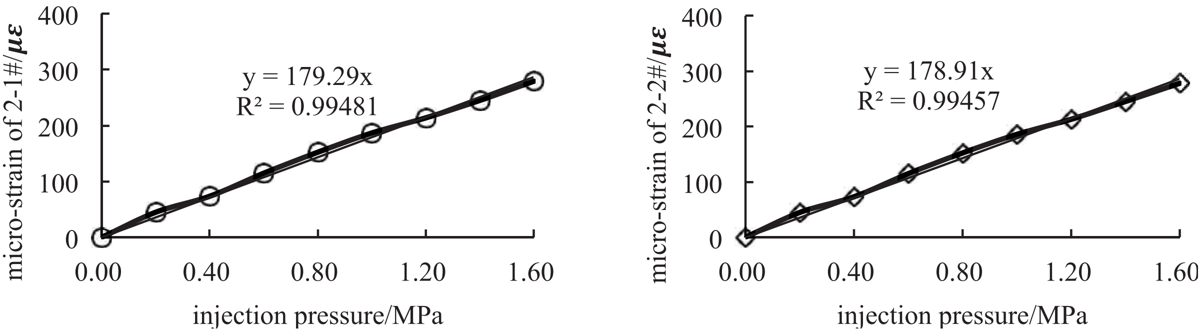


Figure 11. Hoop strain in the axial direction of reaction concrete lining under the injection pressure.

Fig. 9 shows that the hoop strain of the four measuring points on the inner surface of the reaction concrete lining increases linearly under different levels of pressure loading of circular flat jacks, and the slopes of the four measuring points are very close to each other, showing a very good correlation, which is very close to the theoretical value of the deformation. This demonstrates that the four measuring points on the reaction concrete lining deform in a very uniform way under all levels of loading pressure, and the hoop stress they bare is evenly distributed, which means that the flat jacks exert very uniform compressive stress to the reaction concrete lining at the circumferential direction. Fig. 9 and Fig. 11 show that the hoop deformations of 2#, 21#-, and 22#- measuring points were almost identical under all levels of pressure loading of circular flat jacks. This means that the compressive stress generated by circular flat jacks at the axial direction is also well distributed.

Fig. 10 shows that the hoop strain of the three measuring points on the outer surface of the steel plate increases linearly under all levels of pressure loading of circular flat jacks, and the slopes of three measuring points are very close to each other, showing a very good correlation, which is almost identical to the theoretical value of the deformation. Being an elastic material, steel can automatically deform in a coordinated way under stress, but circular flat jacks only serve as a medium of force transmission in the loading test. The force between steel plate and reaction concrete lining is the action and reaction for contact pressure. Therefore, the tensile stresses applied by circular flat jacks to the steel plate are also very well distributed at the hoop direction, which verifies the experimental results.

Based on the above analysis, it can be concluded that the stress applied by the circular flat jacks loading system to both the steel plate and reaction concrete lining is very uniform. So in real projects, this loading system can properly solve the problem of inner water pressure on the pre-stressed concrete lining. In real projects, when steel plate used in the model test is replaced by the pre-stressed concrete lining, we just need to adjust the design length of the arc flat jack and the radius of curvature in line with the tunnel diameter, and the circular flat jacks loading system will keep applying uniform pressure regardless of the lining material or tunnel diameter.

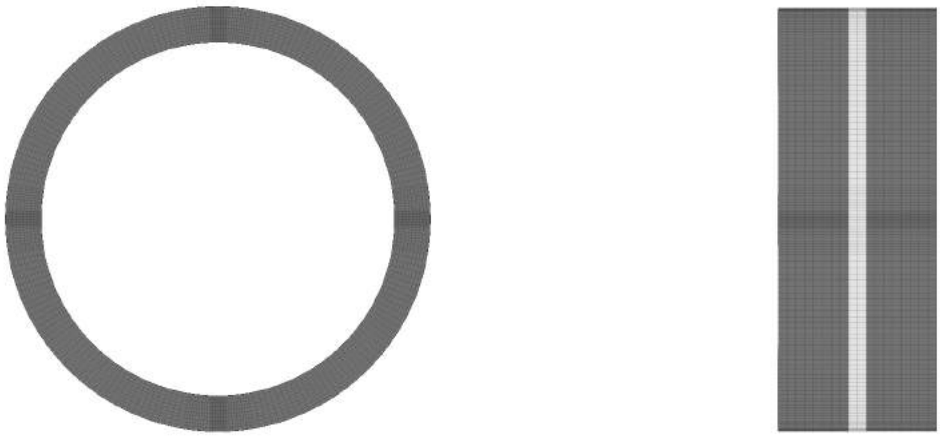
NUMERICAL SIMULATION

For pre-stressed tunnel water pressure simulation test, when designing the circular flat jacks, the tunnel section with loading pressure may be very long in the axial direction, and the tunnel diameter may also be larger than the model. Therefore, when arranging the circular flat jacks, we need to consider the hoop spacing H of the arc flat jacks and the axial spacing L of the circular flat jacks, as shown in Fig. 4. Limited by the size of model test, there is no way to study the change of stress uniformity caused by the change of the circular flat jacks arrangement along hoop and axial direction, while numerical simulation could perfectly solve this problem. Since the force transformation between steel plate and reaction concrete lining is regarded as the action and reaction for the contact pressure, the concrete reaction concrete lining could be used as the object of stress analysis. Using the finite difference software Flac3D for modeling and calculation, we could receive the hoop stress changes of reaction concrete lining under different circular flat jack arrangement along hoop and axial directions.

Numerical model

The numerical model is built as shown in Fig. 12. In the numerical model, hexa-grid with linear elastic constitutive relation is used for counterforce lining; and equivalent load simulation is adopted for circular flat jacks. Equivalent load is applied to the outer surface of the hexa-grid as plane forces.

The parameters for calculation are as follows: inner radius of reaction concrete lining is 1.0m, outer radius is 1.2m, the concrete strength is C40, elastic modulus Ec = 38GPa, Poisson's ratio μ = 0.167, concrete deadweight is 2400kg/m3, and the injection pressure is 1.0MPa. A circular flat jack is composed of four connected arc flat jacks, with the spacing between each being H. The width of the circular flat jack is 0.4m, and the spacing between every two rings in the axial direction is L. (Fig. 4).



(a) The circumferential sectional view (b) The axial sectional view

Figure 12. FLAC^{3D} finite element model.

Simulation of the hoop arrangement

The stress situation of reaction concrete lining was calculated when the arc flat jack hoop spacing H is 0.00m, 0.05m, 0.10m, 0.20m, and 0.30m, respectively, and the corresponding minimum principal stress clouds are shown in Fig. 13. The average values of hoop stress on the inner surface of reaction concrete lining with different hoop spacing are given in Table 2. The following rules are concluded by analyzing the calculation results:

(1) When H = 0.00m, the reaction concrete lining receives evenly distributed external loading by circular flat jacks, and the hoop stress of the inner surface of reaction concrete lining is also well distributed. The stress situation of reaction concrete lining is consistent with the thick cylinder theory, assuming there is only the external water pressure. This demonstrates that the model calculation is correct.

(2) When the arc flat jacks are arranged with hoop spacing, the maximum hoop stress of the inner surface of reaction concrete lining appears in the non-loaded area, and the minimum hoop stress appears in the middle of the single block of arc flat jack, showing certain non-uniformity, which becomes more obvious when the value of H gets larger.

(3) When H = 0.05m, calculation model is consistent with the previous test model, and the hoop stress of the inner surface of reaction concrete lining is uniform. Due to gravity, the minimum hoop stress is about -4.80MPa, which appears in the middle of the arc flat jack at the upper half-ring, and the maximum hoop stress appears in the non-loaded area, which has an average value of -8.30MPa. The average hoop stress of the inner surface of reaction concrete lining is -6.50MPa, which is less than 1%, smaller than the theoretical value -6.55MPa. And the compressive stress distribution of reaction concrete lining is uniform under the model condition, which is consistent with the model test results.

When the water injection pressure is 1.0Ma, the model test and numerical simulation were conducted, and the results of several monitoring points obtained, respectively, from them are listed in Table 3. In the following, the comparisons between model test and numerical simulation were conducted. Because the monitoring point in the model test is located in the non-loaded area (see Fig. 8), the measured value (average of -7.04MPa) and the numerical value (average -8.30MPa) are greater than the theoretical value (-6.55MPa). From Fig. 13 (b), it can be seen that the inner surface of the reaction concrete lining near the non-loaded area is complicated and the pressure value varies greatly along the ring direction. However, the measured hoop stress and numerical calculation hoop stress of the four positions are uniform. In general, the numerical results are closely consistent with the model test results.

(4) When H = 0.10 m, the minimum hoop stress is -4.00MPa, which appears in the middle of the arc flat jack at the upper half-ring, and the maximum hoop stress is -9.80MPa, which appears in the non-loaded area. The average hoop stress of the inner surface of reaction concrete lining is -6.39MPa, which is only 2.4% smaller than the theoretical value -6.55MPa, and the uniformity of hoop stress is attenuated.

(5) The hoop stress of the central circular flat jack decreases with the increase of H. When H = 0.30m, the minimum compressive stress is -2.0MPa, and the maximum compressive stress is -12.0MPa, showing a very uneven distribution of stress.

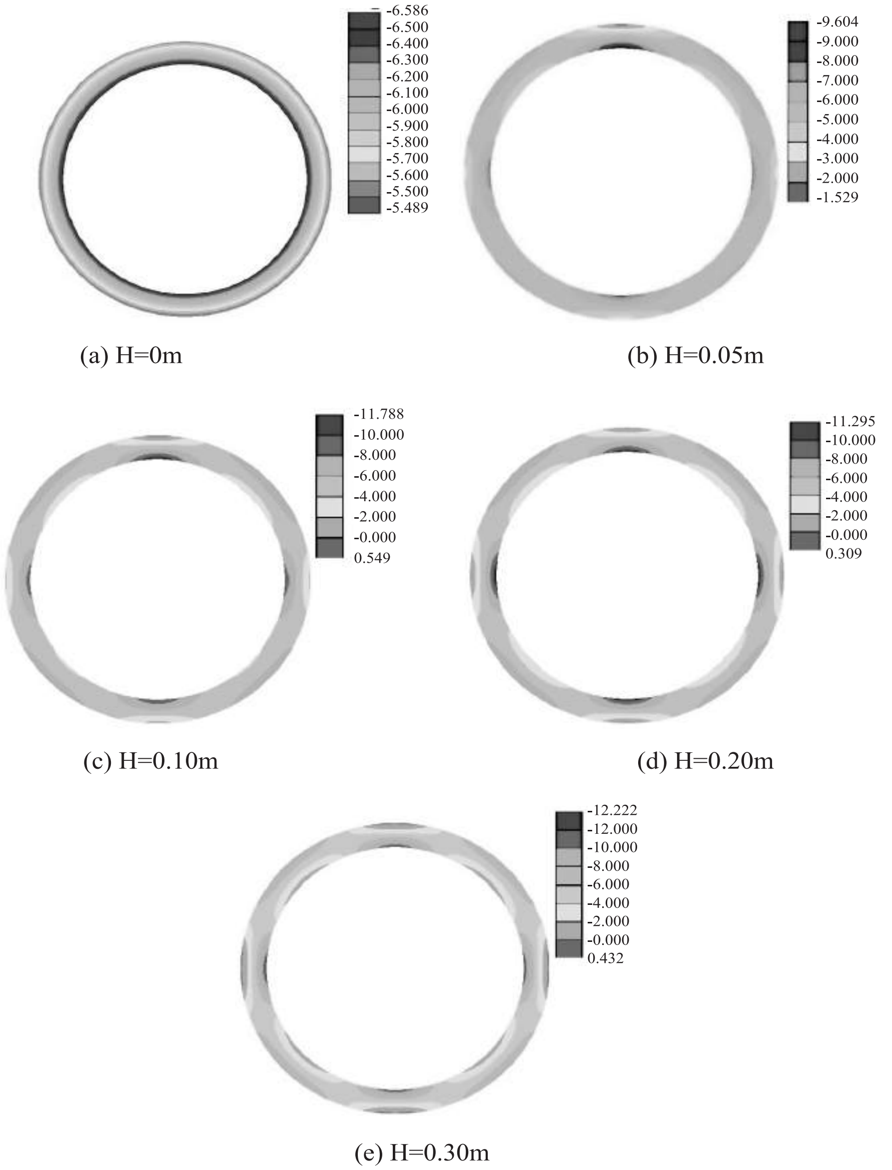


Figure 13. The minimum principal stress cloud with different hoop spacing (MPa).

Table 2. The hoop stress of the inner surface of reaction concrete lining with different hoop spacing of circular flat jacks (MPa).

	Theoretical value	**Numerical calculation value**			
Hoop spacing *H*(m)	0.00	0.05	0.10	0.20	0.30
Average hoop stress σ_θ	-6.55	-6.50	-6.39	-5.64	-4.71

Table 3. The comparison between the model test results and the numerical simulation (MPa).

	The hoop stress value				**The average value**
Monitoring points	1#	2#	3#	4#	
Model test value	-7.20	-6.95	-7.07	-6.95	-7.04
Calculation value	-8.65	-8.04	-8.49	-8.03	-8.30

Table 2 shows that when the uniform load is applied, the stress distribution of the inner surface of reaction concrete lining is uniform. When the hoop spacing is 0.05m, the stress value of the inner surface of reaction concrete lining is 0.8%, smaller than the theoretical average, and when the hoop spacing is 0.10m, the stress value of the inner surface of reaction concrete lining is 2.4%, smaller than the theoretical average. The average stress decreases with growing unevenness, while the hoop spacing H increases. With regard to the tunnel, the larger the ratio of H to the tunnel diameter D, the bigger the proportion of non-loaded area and the smaller the average stress with growing unevenness. Therefore, when designing the circular flat jacks arrangement of a tunnel with certain diameter D, the hoop spacing should be as small as possible to avoid unevenness of stress due to large spacing, which may leave the loading test meaningless. Judging from the above calculation results, using 12 piers to impose load in the Xiaolangdi model test would cause a large stress concentration and hoop stress reduction.

Because the hoop stress will be reduced by the hoop spacing, if loading in the test is done with certain design pressure, the actual loading value will be smaller than the design value. So, to compensate the loss of hoop stress caused by spacing, the hoop stress compensation coefficient $\boldsymbol{\alpha}$ is introduced, in this way:

$$P_{in}=\boldsymbol{\alpha}P_0 \tag{8}$$

where P_{in} is the water injection pressure, read from the water pressure gauge;

P_0 is the design water pressure value;

$\boldsymbol{\alpha}$ is the hoop stress compensation coefficient, as a function of H/D, when H/D=0, ⊠=1.0.

Adjusting water injection pressure by hoop stress compensation coefficient can make up the loss of stress caused by the arc flat jack ring spacing, then the hoop stress value of reaction concrete lining can be consistent with the design water pressure.

Simulation of the axial arrangement

When the hoop spacing H is 0.05m, the stress of reaction concrete lining is calculated when the circular flat jacks axial spacing L is 0m, 0.05m, 0.10m, and 0.20m, respectively. Choosing two sections of circular flat jacks axial length from the calculation model (with a pitch length) to analyze, the corresponding minimum principal stress clouds are shown in Fig. 14. The average values of hoop stress in the inner surface of reaction concrete lining at different axial spacing are given in Table 4.

Fig. 14 shows that with a constant water injection pressure, the hoop stress of the inner surface of reaction concrete lining is more uniform when the circular flat jacks are axially spaced than they are spaced at the hoop direction. The axial stresses of loaded and non-loaded region are almost equal in the calculation of axial extent, but the hoop stress value gradually decreases with the increase of distance L, showing certain non-uniformity.

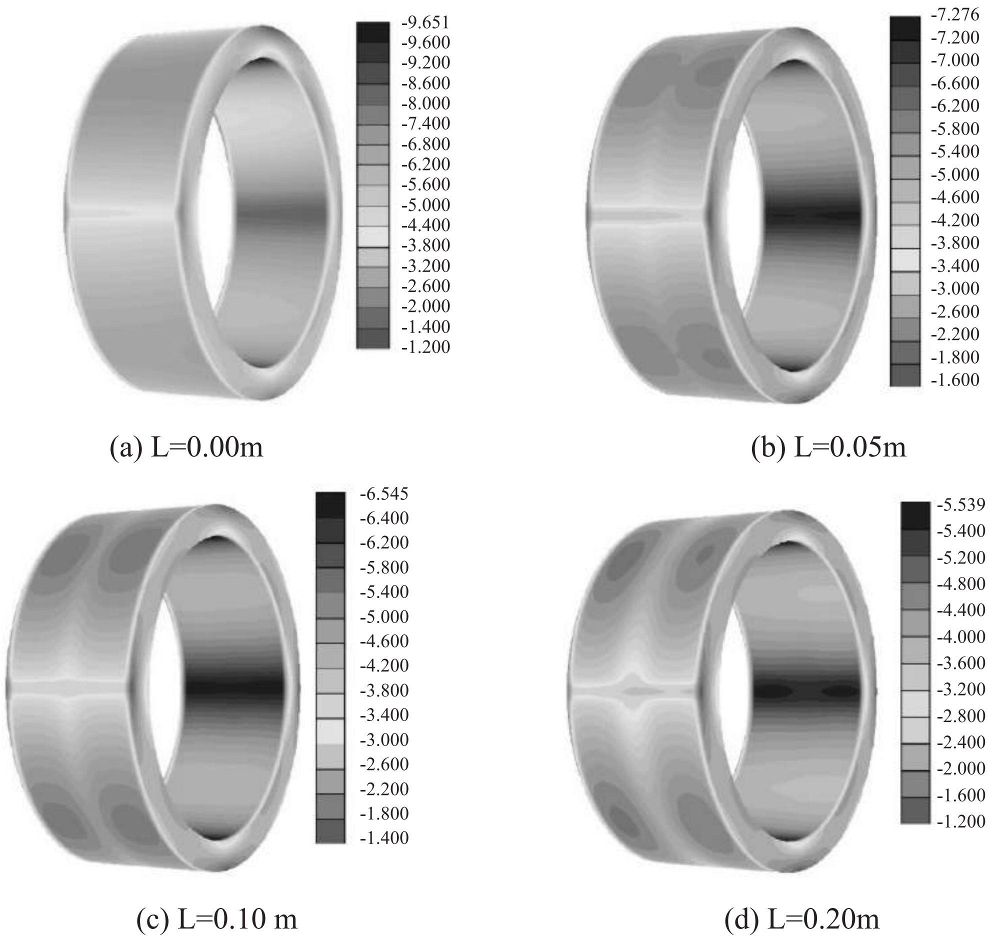


Figure 14. The minimum principal stress cloud with different axial spacing (MPa).

Table 4. The hoop stress of the inner surface of reaction concrete lining with different axial spacing of circular flat jacks (MPa).

	Theoretical value	**Numerical calculation value**			
Axial spacing *L*(m)	0.00	0.00	0.05	0.10	0.20
Average hoop stress σ_θ	-6.55	-6.50	-6.25	-5.97	-4.86

Table 4 shows that the average hoop stress of the inner surface of reaction concrete lining decreases when the axial spacing gets larger; when the axial spacing is 0.05m, the average stress value of the inner surface of reaction concrete lining is 3.8%, smaller than the theoretical average, and when the axial spacing is 0.20 m, the average stress value of the inner surface of reaction concrete lining is 25.2%, smaller than the theoretical average. The larger the spacing, the steeper the fall of average stress value. As regards the tunnel, the larger the ratio of the axial space L to the circular flat jack width B, the larger the proportion of the non-loaded area, and the smaller the average stress.

Because the hoop stress will be substantially reduced by the axial spacing, if the circular flat jacks are axially spaced in the test and loading with certain design pressure, the actual loading value will be much smaller than the design value. Therefore, to compensate the loss of hoop stress caused by axial spacing, axial stress compensation coefficient $\boldsymbol{\beta}$ is introduced, and equation (8) is amended, in this way:

$$P_{in}=\boldsymbol{\alpha\beta}P_0 \tag{9}$$

where P_{in} is the water injection pressure, read from the water pressure gauge;

P_0 is the design water pressure value;

$\boldsymbol{\alpha}$ is the hoop stress compensation coefficient, as a function of H/D, when H/D=0, $\boldsymbol{\alpha}$=1.0. $\boldsymbol{\beta}$ is the axial stress compensation coefficient, as a function of L/B, when L/B=0, $\boldsymbol{\beta}$=1.0. Adjusting water injection pressure by hoop and axial stress compensation coefficient can compensate the loss of stress caused by the circular flat jacks ring spacing, then the hoop stress value of reaction concrete lining can be consistent with the design water pressure.

When designing the circular flat jacks loading test, the parameters of circular flat jacks should be firstly determined according to the tunnel and lining parameters, and then the hoop and axial stress compensation coefficient should be calculated to adjust the water injection pressure in accordance with the design pressure values, and finally the loading test could be carried out.

CONCLUSIONS

The new type of circular flat jacks loading system to simulate the water pressure of pre-stressed concrete lining is introduced in this paper. The loading effect of circular flat jacks loading system is verified by a model test and numerical analysis. The internal water pressure simulation effects with different design parameters are received through numerical simulation, and the following conclusions are achieved:

(1) The circular flat jacks loading system is proposed; the effect of loading system applying uniform pressure is verified by a model test. The results demonstrate that using the loading system of circular flat jacks to apply the force can simulate the force characteristics of internal water pressure very well, and the forces on pre-stressed concrete lining and reaction concrete lining are both uniform.

(2) According to the theory of elasticity mechanism, the calculation method for radial and circumferential deformation margin is obtained in circular flat jack design. Both are the inverse function of elastic modulus. For high-strength grade concrete lining, it is very easy to implement deformation margin of circular flat jack in processing.

(3) When the arc flat jacks are installed in the hoop direction, the average hoop stress of reaction concrete lining will be reduced, and the unevenness will increase, while the hoop spacing increases. When the circular flat jacks are installed in the axial direction, the average hoop stress value of the reaction concrete lining decreases remarkably with the increase in axial spacing. When the axial spacing is 0.2m, the axial stress is uniform, but the average stress value is reduced by 25.2%.

(4) Based on the numerical results, this paper proposes that when designing the circular flat jacks loading test, the hoop and axial stress compensation coefficient should be calculated to adjust the water injection pressure in accordance with the design pressure values.

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نظام تحميل مبتكر لتطبيق الضغط الداخلي على نموذج اختبار لبطانة خرسانية مسبقة الإجهاد في أنفاق الضغط

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** مختبر الدولة الرئيسي الصيني لمحاكاة وتنظيم دورة المياه في حوض النهر، المعهد الصيني للموارد المائية وبحوث الطاقة المائية، بكين، 100038، الصين

الخلاصة

غالباً ما تُستخدم البطانات الخرسانية مسبقة الإجهاد في الأنفاق التي تتعرض لضغط مياه داخلي. تُعتبر نماذج الاختبار مهمة لتحقيق فهم أفضل لأدائها. ونقدم هنا نظام تحميل مبتكر لتطبيق الضغط الداخلي على مثل هذه البطانات. ويتكون نظام التحميل من مرافع مسطحة دائرية داخل بطانة الخرسانة مسبقة الإجهاد وهي عبارة عن بطانات من الفولاذ. يمكن توليد ضغط موحد عن طريق تضخيم البطانات الفولاذية مقابل البطانة الخرسانية مسبقة الإجهاد والبطانة الداخلية للخرسانة. وتعمل البطانة الداخلية كدعامة تفاعلية. وفي هذا البحث، تمت مناقشة مبادئ التصميم وتفاصيل التصنيع لهذا النظام، وأظهرنا بعض نتائج الاختبار لها.