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Experimental and numerical investigation on bearing mechanism and capacity of new concrete plug structures

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Abstract. The stability and safety of concrete plug structure of diversion tunnel is crucial for the impoundment of upstream reservoir in hydropower projects. The ongoing Wudongde hydropower plant in China plans to adopt straight column plugs and curved column plugs to replace the traditional expanded wedge-shaped plugs. The performance of the proposed new plug structures under high water head is then a critical issue and attracts the attentions of engineers. This paper firstly studied the joint bearing mechanism of plug and surrounding rock mass and found that the quality and mechanical properties of the interfaces among plug concrete, shotcrete, and surrounding rock mass play a key role in the performance of plug structures. By performing geophysical and mechanical experiments, the contact state and the mechanical parameters of the interfaces were analyzed in detail and provide numerical analysis with rational input parameters. The safety evaluation is carried out through numerical calculation of plug stability under both construction and operation period. The results indicate that the allowable water head acting on columnar plugs is 3.1 to 7.4 times of the designed water head. So the stability of the new plug structure meets the design code requirement. Based on above findings, it is concluded that for the studied project, it is feasible to adopt columnar plugs to replace the traditional expanded wedge-shaped plugs. It is hoped that this study can provide reference for other projects with similar engineering background and problems.

Keywords: new plug structure; straight column plug; curved column plug; numerical simulation; bearing mechanism; adaptability evaluation

1. Introduction

The diversion tunnels of hydropower plants are designed to convey water from the upstream of a river to its downstream side during the excavation of dam foundation and the construction of dam. The concrete plug is used to seal the diversion tunnels before the impoundment of upstream reservoir (Gan 2000). During operation period, the plug structure is designed to integrate with surrounding rocks and jointly bear the water pressure caused by the upstream water head. In the design of a diversion tunnel plug, the safety design level is required to be equivalent to the major hydraulic structures such as the dam (Gan 2001). Therefore, the safety of the plug and its surrounding rocks in operation period are extremely important. The diversion tunnel plugs are used to block upstream reservoir water, so as to raise the water level for power generation purpose. Due to the unique function of plug structures, not only their stability is crucial for the whole project, but also whether the sealing of diversion can be completed on time is of great significance to subsequent construction procedures and the economic benefits of the project.

Despite the importance of the plug structures for the hydropower plants, the design of a plug in China nowadays is always designed based on engineering experiences (Dong *et al*. 2011, Yang *et al*. 2007, Yin *et al*. 2008) obtained from other completed projects with similar boundary conditions. The reason lies in the fact that the current Chinese design codes (The Standard Compilation Group of the National Energy Administration of People's Republic of China, 2014, The Standard Compilation Group of the Ministry of Water Resources of People's Republic of China 2016) lack clear guidance and regulation on the design of this hydraulic structure and only give general principles and basic methods. For example, the codes suggest that the type of plugging body should be determined according to the cross-section shape of tunnel, construction conditions, engineering geological conditions and other factors. The codes also suggest that the shape of a plug should preferably be expanded wedge-shaped, and for plugs designed to withstand high water pressure, numerical methods should be considered to perform a more elaborate and prudent evaluation.

However, the widely adopted expanded wedge-shaped plugs have some drawbacks, which may lead to the delay in construction process and the increase of project cost. As the expanded wedge-shaped plugs requires a larger cross-section of the tunnel, the surrounding rock mass at the plug section has to be re-excavated to enlarge the profile of cross-section after the tunnel excavation which was carried out during the construction period. In addition, the lining

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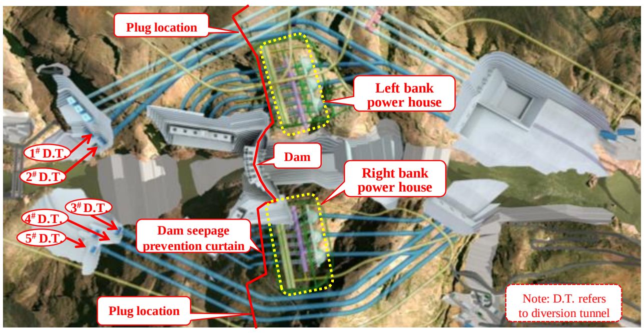
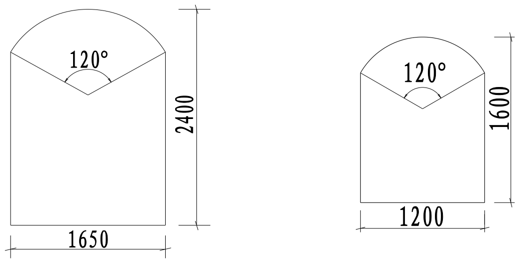


Fig. 1 Location of diversion tunnels and their plugs



(a) 1#~4# tunnels (b) 5# tunnel

Fig. 2 Profile of the diversion tunnels

structures that have already been poured will be removed. Such re-excavation not only brings damage to surrounding rock mass (Zhang *et al*. 2018), but also undermines the integrity of lining structures. Moreover, the re-excavation also causes damage to the completed anti-seepage curtain of the dam. As the reinforcement and anti-seepage treatment of the contact areas between the plug and the surrounding rocks is difficult, the construction time for plug structure becomes more tense and it is more difficult to meet the time requirement for completing the construction of plug

In view of the above mentioned various problems of the traditional wedge-shaped plugs, it is necessary to propose a new plug structure that can effectively address these engineering concerns. It is well recognized that the design of the traditional wedge-shaped plug is empirically sophisticated and its reliability has been verified by many projects (Yang and Guo 2008, Zhang and Zou 2002). Compared to the traditional wedge-shaped plugs, a new plug structure type lacks demonstration examples and engineering experience. Many scholars have conducted extensive research on concrete materials (Lv *et al*. 2015, Kim and Kwak 2017) and structures (Nguyen and Nguyen. 2016, Tang *et al*. 2015, Gharehbaghi 2018) through various means, including experiments (Bu *et al*. 2018, Hashemi and Mosalam 2006), analytical analysis (Yan *et al*. 2015, Falamarz-Sheikhabadi and Zerva 2017), numerical simulation (Mao *et al*. 2014, Heidari *et al*. 2018), and other advanced technique (Ebrahimi *et al*. 2018), to prove the feasibility and reliability of their new ideas. These researches show that, for a newly proposed concrete structure, it is necessary carry out extensive demonstrations regarding various concerned aspects. In this paper, the new concrete structure refers to a non-traditional plug which is able to avoid problems with traditional expanded wedge-shaped plugs. Therefore, a series of verification work should be conducted, including the structural design features, bearing force mechanism, material and interface mechanical parameters and the overall safety reserve. Only by answering a series of questions that the engineering design is concerned with can the engineers ensure the new plug type has sufficient reliability.

Firstly, the mechanism of the combined bearing capacity of different types of plug structures and surrounding rocks is analyzed, and the safety of different plug structures is evaluated. The contact state between the plug and the surrounding rocks and the mechanical parameters describing this contact state are then verified by geophysical and experimental investigation. On this basis, the adaptability of the new plug structures of Wudongde diversion tunnel is analyzed at last, which provides scientific basis and technical support for the design of plug structures, ensures the safety of the plug structures during operation periods, and provides similar projects with a reference.

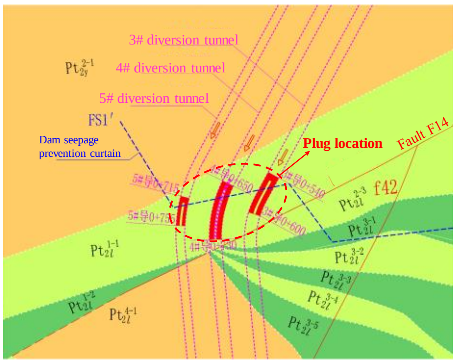
2. Analysis of the bearing mechanism of different types of plugs

2.1 Engineering background of the new plug structure

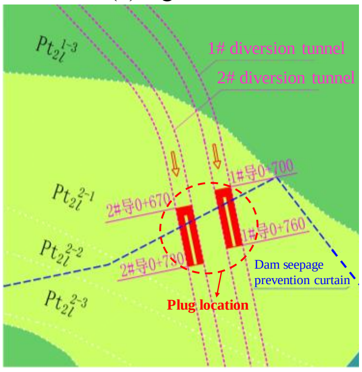
Wudongde hydropower plant is the most upstream of the four cascaded stages in the lower reaches of Jinshajiang River. The water retaining structure is a double-curved arch dam. The normal water storage level of the reservoir is 975.0 m, the total storage capacity is 7.408 billion m^3, the dam crest elevation is 988.0 m, the maximum dam height is 270 m, and the total installed capacity is 10200 MW.

The main hydraulic structures contains the left and right underground powerhouses, the dam, the headrace and tailrace tunnels, and the diversion tunnels (Fig. 1). A total of 5 D-shaped diversion tunnels are arranged in the project, 1# and 2# diversion tunnels are arranged on the left bank, and 3#, 4# and 5# diversion tunnels are arranged on the right bank. The cross-section dimension of the 1#~4# diversion tunnel is 16.5 m×24 m (Fig. 2(a)); the cross-section dimension of the 5# diversion tunnel is 12 m×16 m (Fig. 2(b)).

The geological conditions for the plug structures are basically favorable for placing plug structures (Fig. 3). The geological formation of 1# and 2# diversion tunnels on the left bank is the first subsection of the second section of the Luoxue group (Pt_{21}^{2-1}). The lithology is gray-white interbedded to medium-thick layer sandwiched and thick-layered marbled dolomite. The angle between the orientation of rock formation and the longitudinal axis of diversion tunnels is about 50°-60°. The rock masses for the planned plug location is slightly weather and there is no geological faults found at the area. There are two groups of joints and fractures in rock masses. The rock mass is classified as the third level of rock mass (there are five levels in total, and the first level is the best) according to the engineering classification of rock masses (The National Standards Compilation Group of the People's Republic of China 2015).

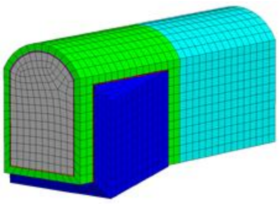


(a) right bank

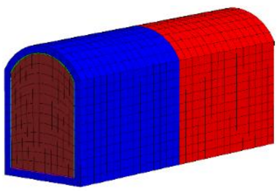


(b) left bank

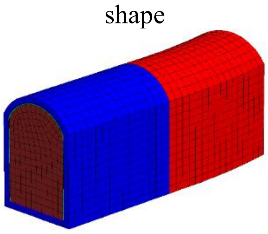
Fig. 3 Plug location of diversion tunnels and their geological rock formation



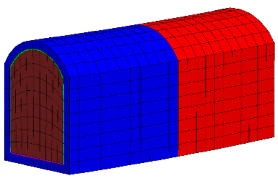
(a) traditional expanded wedge shape



(b) straight column shape



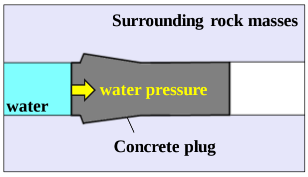
(c) curved column and straight column combined shape



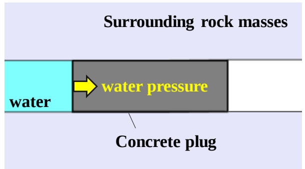
(d) curved column shape

Fig. 4 Design for different types of concrete plug structures

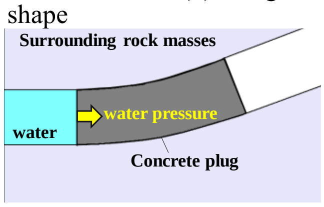
The geological formation of 3#, 4#, and 5# diversion tunnels is the first subsection of the first section of the Luoxue group (Pt_{21}^{1-1}). The lithology of 3# diversion tunnel is gray interbedded to thin layered limestone and dolomite and the lithology of 4# and 5# diversion tunnels are gray interbedded thin layered limestone. The angle between the orientation of rock formation and the longitudinal axis of diversion tunnels is about 30°-52°. The rock masses for the planned plug location is fresh. There is no geological fault found in 3# and 5# diversion tunnels but a small-scale fault is found in 4# diversion tunnel. The rock mass of 3#



(a) traditional expanded wedge shape



(b) straight column shape



(c) curved column shape

Fig. 5 Plane view of different concrete plugs describing the loading conditions

diversion tunnels is classified as the third level and that of 4# and 5# diversion tunnels is classified as the fourth level.

In order to explore the adaptability of the new plug structures, based on the traditional expanded wedge-shaped plug schemes (Fig. 4(a)), the schemes of non-expanded straight column shape (Fig. 4(b)), the curved column and straight column combined shape (Fig. 4(c)), and the curved column shape plug (Fig. 4(d)) structures are proposed. The different colors for each type of plus refer to different stages of pouring the concrete plug. The concrete poured at each stage will be subjected to quality inspection to guarantee its integrity and bearing capacity. According to the designed location of the diversion tunnel plug, the 1# and 2# diversion tunnel plugs of the left bank consist of traditional expanded wedge-shaped plug scheme and non-expanded straight column plug scheme. These two schemes are intended for comparison purpose. The 3#~5# diversion tunnel plugs of the right bank also consist of traditional expanded wedge-shape scheme and new plug scheme. The new plug scheme takes advantage of the arc tunnel section of the longitudinal tunnel axis and contains a curved column and straight column combined plug and a curved column plug.

2.2 Joint bearing mechanism of plug and surrounding rocks for various plug types

The characteristics of the various plug design schemes given in Fig. 5 are analyzed, and the plug type can be divided into three types: expanded wedge shape, straight column shape and curved column shape. The curved column and straight column combined plug is a composite plug with the characteristics of a straight column and a curved column. The joint bearing mechanism of plug and surrounding rocks for different plug types is associated with the mutual interaction between the plug structure and surrounding rocks as well as their mechanical response characteristics. The interaction effects between the plug and the surrounding rock are summarized as below.

For the straight column plugs, the plug-surrounding rock interaction is mainly reflected by the shearing effect and the Poisson effect. The shear effect refers to the shear resistance

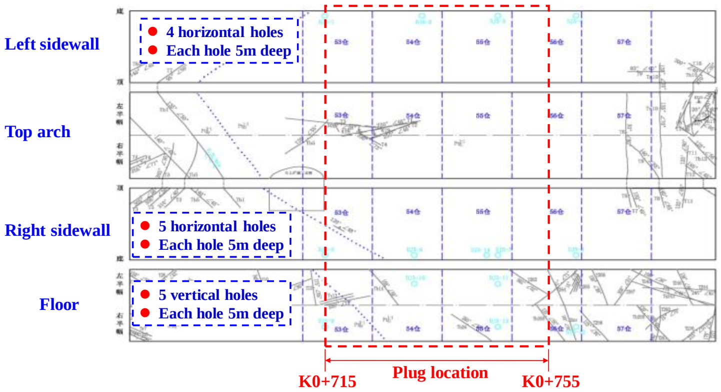


Fig. 6 Program of field tests plotted in a plan view of the 5# diversion tunnel

provided by the interface of plug concrete and shotcrete and the interface of shotcrete and surrounding rock. The Poisson effect means that under the action of external water pressure, the plug bears compressive stress along the direction of the flow, so that the plug deforms laterally occurs in the direction perpendicular to the flow and forms a compression effect on the surrounding rocks. In this way, the normal force acting on the interface of plug and surrounding rock is increased, thus generating additional frictional resistance against sliding.

For the curved column plugs, the interaction of plug and surrounding rock not only contains the shearing effect and the Poisson effect, but also includes the bending effect due to the curved shape of the column. That is, there is an angle between the direction of the external water pressure acting on the plug and the potential sliding direction of the plug, which not only causes the external water pressure to form a load component perpendicular to the direction of the water flow, but also causes the plug to be subjected to a bending moment, thereby producing a bending effect. Thus, the additional frictional resistance of the outer side wall of the curved column plug is increased, so a greater anti-sliding effect than the straight column plug is present.

For the wedge-shaped plug, the interaction of plug and surrounding rock not only contains the shearing effect and the Poisson effect, but also has the wedge effect formed by the wedge-shaped expanded excavation. That is, the water pressure is passed to the surrounding rock through the wedge-shaped plug, so that the surrounding rock around the excavation directly bears a part of the water pressure. Because the shearing capacity of the surrounding rock mass is higher than that of the interface of shotcrete and surrounding rock mass, the wedge effect increases the ability of the plug to bear load.

It can be seen that in above various interactions between plug and surrounding rock mass, the shear effect is directly related to the shear performance of the interface of plug concrete and shotcrete and the interface of shotcrete and surrounding rock mass. The Poisson effect and the curved section effect increase the anti-sliding force by increasing the normal force acting on the interface, which is indirectly related to the shear performance of the interfaces. The wedge effect directly provides the anti-sliding force by utilizing the shear properties of the surrounding rock mass medium near the excavation surfaces.

From the qualitative analysis of the joint bearing mechanism of different types of plugs, the bearing capacity of various types of plugs can be preliminarily evaluated. That is, when other conditions are the same, the anti-sliding ability of the wedge-shaped plugs are the largest, the curved-column plugs are the second, and the straight column plugs are the smallest.

3. Experimental investigation on mechanical properties of interfaces among plug concrete, shotcrete and surrounding rock mass

3.1 An outline of the experimental investigation

It is known from the above analysis that, the bearing capacity of curved column plug and straight column plus mainly depends on the shear performance of the interface of plug concrete and shotcrete and the interface of shotcrete and surrounding rock mass. Therefore, the applicability of new plug structures is closely associated with the mechanical properties, especially the shear performance of interfaces among plug concrete, shotcrete, and surrounding rock mass. Considering that the construction quality of the interfaces during the plug construction is uncertain, in order to provide reliable mechanical parameters for the design of different types of plugs and rationally determine the length of plug, experimental investigations of the mechanical properties of the interfaces among plug concrete, shotcrete and surrounding rock mass were carried out at the diversion tunnel plug section of Wudongde hydropower plant.

The permanent plug section (K0+715~K0+755) of the 5# diversion tunnel on the right bank was used as the test area, and 14 inspection holes are arranged in the tunnel floor and the left and right side wall parts (Fig. 6). Among them, there are 4 horizontal holes on the left side wall of the tunnel, 5 horizontal holes on the right side wall, and 5 vertical holes on the bottom plate. The depth of each hole is 5m. Various tests are carried out, including core drilling, geophysical sound wave detection, in-hole TV, plane ultrasonic transverse wave imaging, geological radar detection of backfill grouting, and laboratory tests on rock mechanical properties.

3.2 Result analyses

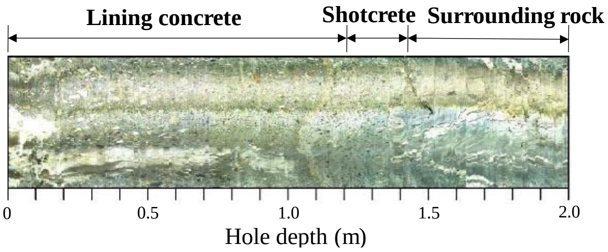


Fig. 7 In-hole TV imaging for a horizontal hole on left sidewall

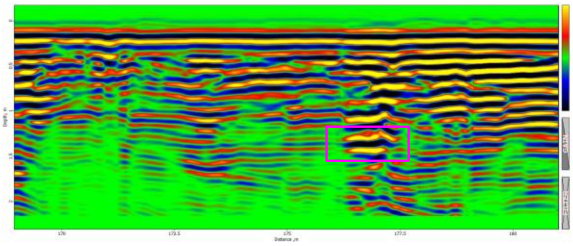


Fig. 8 Results of geological radar detection performed on top arch of 5# diversion tunnel

3.2.1 Properties of interfaces among plug concrete, shotcrete and surrounding rock

Fig. 7 shows the core sample of the horizontal drilling core on the left wall and the in-hole TV imaging.

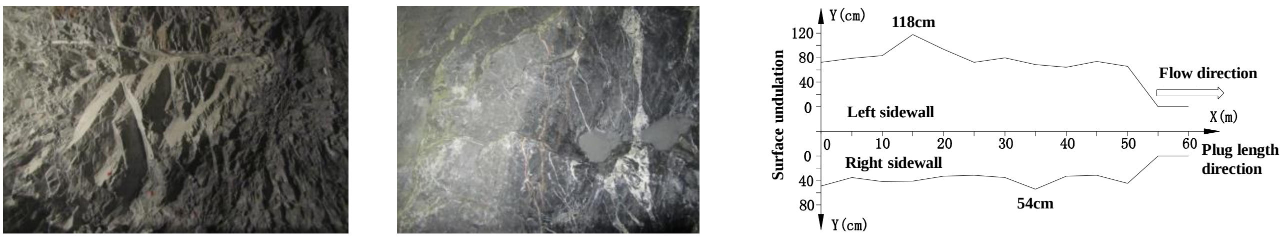
For the floor area, it can be seen that the joint between the lining and the surrounding rock mass is tight and well cemented. There is no weak infillings and opening of the contact surface. The drilling core sample indicates that the rocks are fresh and no corrosion is found. Bedrock accounts for 86.4% of cross-section area of core sample. Bedrock and lining are in close contact and well cemented. No weak infillings or opening are found at contact surfaces.

For the sidewall area, there is also no obvious weak infillings and opening of the joint between the concrete and the surrounding rock mass. The interfaces are generally in tight cementation state, but the contact tightness is slightly worse than the floor area. The interface of lining and shotcrete are in close contact and well cemented, and there is no opening of the contact surface. The drilling core sample indicates that the rock cores are fresh and no corrosion is found. Bedrock accounts for 51.3% of cross-section area of core sample on the left sidewall and the value is 80.8% on the right sidewall. The contact among lining, shotcrete and surrounding rock mass is tight and no obvious weak infilling or opening are found. According to planar ultrasonic imaging results, void between shotcrete and surrounding rock mass is found at 11 locations and it is mainly affected by steel mesh of shotcrete. The total area of void is 1.464 m^2, accounting for 1.46% of detection area. The contact between lining and shotcrete is good.

3.2.2 Acoustic wave velocity characteristics at the plug section

For the lining of the floor of the diversion tunnel, the wave velocity of the bedrock and its junction area is distributed between 4000 and 5000 m/s. For the lining of the sidewall, shotcrete, bedrock and its boundary section wave velocity is distributed between 3800-5200 m/s. From the lining to the surrounding rock mass, the wave velocity distribution generally shows a law of decreasing first and then increasing.

The wave velocity magnitude of the lining and the surrounding rock mass itself is higher. The wave velocity magnitudes of the interfaces among concrete, shotcrete, and surrounding rock mass are relatively low. The reason can be attributed to two points. First, the concrete material used for shotcrete is lower in strength than lining structures and then reduces the sonic wave velocity. Secondly, the mechanical properties of the junctions of different materials depend on the bonding properties of the materials, and their strength is obviously slightly lower than the strength of the materials themselves.



(a) sidewall (b) floor (c) a sketch of surface fluctuation

Fig. 9 Surface conditions of surrounding rock mass after tunnel excavation: the left diversion tunnels

(a) sidewall (b) floor (c) a sketch of surface fluctuation

Fig. 10 Surface conditions of surrounding rock mass after tunnel excavation: the right diversion tunnels

3.2.3 Geological radar detection of backfill grouting

The backfill grouting is specially designed for top arch area where the contact between concrete and surrounding rock mass is the most likely to open. Fig. 8 plots the results of geological radar detection performed on top arch of 5# diversion tunnel. Results from the 5 diversion tunnels show that for most parts of the backfill grouting, the grouting effect achieves favorable level and no obvious opening between lining concrete and surrounding rock mass is found.

The acoustic wave velocity detection results show that the wave velocity of surrounding rock mass before grouting ranges from 4205 m/s to 4564 m/s, while the value after grouting ranges from 4351 m/s to 4786 m/s, indicating a growth of 3.32%-5.8%.

3.2.4 Laboratory test results and recommended values of shear strength parameters

Fig. 9 and Fig. 10 give the surface condition of surrounding rock mass after tunnel excavation. It is discovered that the excavation surfaces are rough with high undulation, thus enhancing the shear strength of the interface between surrounding rock and lining concrete after pouring the concrete.

Through core drilling, the core samples reflecting the contact state of concrete and shotcrete and the contact state of shotcrete and surrounding rock mass can be obtained. Laboratory shear test was performed on these core samples. The results show that for the contact area of lining concrete and shotcrete, the mean value of internal frictional coefficient is 1.204, and the mean value of cohesion is 7.842 MPa. For the contact area between shotcrete and surrounding rock mass, the mean value of internal friction coefficient is 1.33, and the cohesion is 5.79. It can be seen that the shear strength obtained in laboratory is high. The mechanical parameters of the interfaces among lining concrete, shotcrete, and surrounding rock mass are suggested as: the interface between surrounding rock mass and lining concrete at floor area: the internal friction coefficient is 0.9 to 1.1, the cohesion is 0.9 MPa to 1.1 MPa; the interface between surrounding rock mass and shotcrete at sidewall area: the internal friction coefficient is 0.8 to 0.9, the cohesion is 0.7 MPa to 0.9 MPa; the interface between shotcrete and lining concrete at sidewall area: the internal friction coefficient is 0.9, the cohesion is 0.9 MPa.

The recommendations are made based on several considerations as below.

(1). There is a size effect of the test results obtained in laboratory test, which makes the shear strength larger than the data obtained from field tests.

(2). The data that are adopted in safety evaluation should reserve a sufficient safety margin.

(3). The shear strength of rock masses obtained in the field test at the feasibility study phrase of this project is used for reference.

3.3 Determination of plug length based on limit equilibrium method

The design of plug length is another important aspect of plug design. It is intuitively clear that longer plug produces larger resistance against sliding but also brings higher costs. Therefore, a rational design of plug length requires an elaborate consideration of interface mechanical differences at different areas around the plug in diversion tunnel.

Table 1 Adopted shear strength parameters of interfaces for calculation of permanent plug length

Location	1# and 2# diversion tunnel		3# diversion tunnel		4# diversion tunnel		5# diversion tunnel	
	f'	c' (MPa)	f'	c' (MPa)	f'	c' (MPa)	f'	c' (MPa)
Sidewall	0.7	0.7	0.6	0.6	0.5~0.6	0.5~0.6	0.6	0.6
Floor	1.0	1.0	0.9	0.9	0.7~0.9	0.6~0.9	0.9	0.9

The bearing load characteristics of interfaces are different depending on their specific locations. For the interface of surrounding rock mass and lining concrete, the floor area directly bears the gravitational load of plug, the sidewall area bears a certain amount of normal compressive load due to Poisson’s effect when water pressure is acting on the plug, and the top arch area bears very small amount of load or even zero load because the interface may open under the gravitational load or other factors. Therefore, appropriate mechanical parameters should be assigned to different part of interfaces around the plug, depending on the specific contact state. Table 1 gives the adopted values of shear strength when calculate the length of permanent plug structures for 1#~5# diversion tunnels. These adopted values not only consider the suggested mechanical parameters suggested in section 3.2.3, but also take into account the specific geological conditions for each diversion tunnel. By compare the shear strength values suggested in section 3.2.3 and listed in Table 1, it is found that the finally adopted values of shear strength for interfaces, are on one hand no bigger than the suggested values, and on other hand reflecting geological variations of different diversion tunnels.

The ultimate limit state method recommended by Chinese design codes is adopted to calculate the length of plug. It is a general principle based on limit equilibrium method and the basic calculation formula is

$$\gamma_0 \psi S(\cdot) = \frac{1}{\gamma_d} R(\cdot) \tag{1}$$

where γ_0 is the importance factor of structure, ψ is the factor of design situation. The two factors considers persistent design situation and transient design situation, respectively. γ_d is the structural factor. $S(\cdot)$ and $R(\cdot)$ are the load effect function and resistance function, respectively. With respect to the plug structure, the load effect function $S(\cdot)$ and resistance function $R(\cdot)$ are

$$S(\cdot) = \sum P \tag{2}$$

$$R(\cdot) = f' \sum W + c'A \tag{3}$$

where ΣP is the water pressure acting on the plug structure, ΣW is plug gravity, A is the contact area between plug and surrounding rock mass, excluding of top arch area. Table 2 summarizes the calculation schemes and partial factors considered in each scheme. Table 3 gives the calculation

Table 2 Schemes and partial factors for calculation of plug length

Schemes	Load combination	Condition	γ_0	ψ	γ_d	Partial factors			
						Shear	Cohesion	Gravity	Hydrostatic pressure
Design	Basic	Persistent	1.1	1.0	1.5	1.7	2.0	1.0	1.0
Check	Occasional	Transient	1.1	0.85	1.5	1.7	2.0	1.0	1.0

Table 3 Calculation results of plug length of 1# and 2# diversion tunnels

Diversion tunnel	Load combination	Load or resistance (unit: kN)		Length of plug (m)	
		$\gamma_0\psi S(\cdot)$	$R(\cdot)/\gamma_d$	Calculation result	Adopted length
$1^{\#}$	Basic	816560	824709	44.5	60.0
	Occasional	723236	732116	39.5	
$2^{\#}$	Basic	819491	824709	44.5	60.0
	Occasional	725727	732116	39.5	

result of plug length corresponding to 1# and 2# diversion tunnels. To consider a safety reserve and also to facilitate plug construction, the finally adopted plug length for 1# and 2# diversion tunnels is both 60 m. The plug length for 3#, 4# and 5# diversion tunnels is likewise calculated and the results show that the minimum length for these three tunnels is 48 m, 61 m and 33.5 m, respectively. The adopted length in final design is 60 m, 80 m, and 40 m, respectively. The extension of design length of plugs compare to their calculated length is to consider a sufficient safety margin for structures.

4 Numerical investigation of deformation and stress characteristics of different plugs and adaptability evaluation of the new plug structure

4.1 Overview

The deformation and stress characteristics of different types of plug structures under design load, as well as the overload capacity and safety margin of the plug are further studied so as to evaluate the adaptability of the new plug structure. Based on the analysis of the plug bearing mechanism and the mechanical assessment of interfaces among lining concrete, shotcrete, and surrounding rock mass, as well as the design length of plug, the numerical calculation models of different types of plugs are established by three-dimensional numerical simulation method, and the mechanical response characteristics and adaptability are studied. The research includes three-dimensional numerical calculations of different plug structures and their comparison analysis.

Firstly, numerical calculation models of different types plug structures are established. Then, for each type of plug structure, the calculation of initial geo-stress, the calculation of excavation and support for diversion tunnels, the calculation of pouring plug concrete, and the calculation of external water acting on the plug are performed one by one. After that, comparisons are done on results of different types of plug structures regarding their deformation and stress characteristics. In order to look into the safety condition of different types of plug, the overload method is used to study the progressive failure laws of the interfaces between surrounding rock mass and plug concrete. Finally, based on these calculation and analysis findings, an adaptability evaluation is proposed for the new plug structures.

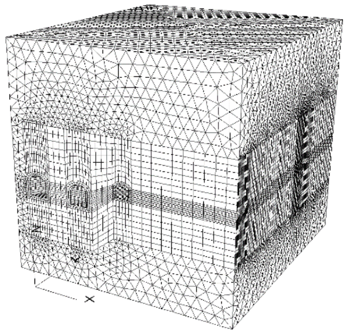


Fig. 11 Calculation mesh

Table 4 Input mechanical parameters for surrounding rock mass and concrete

Surrounding rock mass class	Deformation modulus E (GPa)	Bulk density γ (kN/m^3)	Poisson's ratio	Shear strength		Tensile strength R_t (MPa)
				f	c (MPa)	
III1	16	27.6	0.26	1.1	1.3	0.55
III2	9	27.4	0.28	0.9	0.9	0.30
Concrete plug	20	24.0	0.167	1.1	1.3	1.5

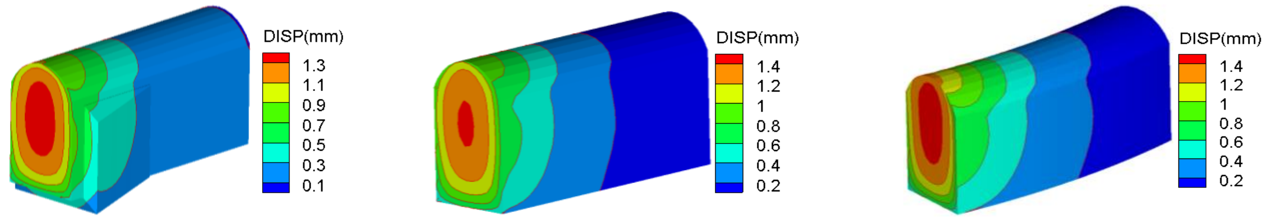
4.2 Calculation mesh

Fig. 11 plots the overall calculation model. Its dimension is 300 m×330 m×300 m along X, Y, and Z axes, respectively. The X axis is perpendicular to the axis of the diversion tunnel; the Y axis is parallel to the direction of the water flow and is positive toward the downstream direction; the Z axis is vertically upward and the bottom elevation of the model is 700 m.

The mesh contains expanded wedge-shaped plug and straight column plug, which are traditional plug type and new plug type, respectively, and intended for comparison purpose. Other new types of plug, which are curved column and straight column combined shape, curved column shape, and curved column shape, are also included. The plug lengths for 1#~5# diversion tunnels in the calculation meshes are 60m, 60m, 60m, 80m, and 40m, respectively.

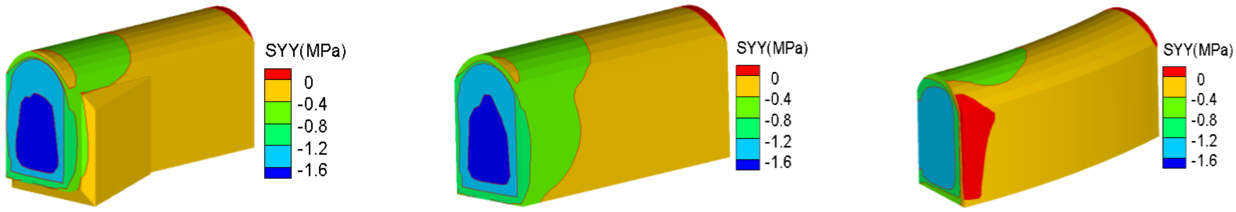
4.3 Input parameters for calculation

Table 4 gives the input mechanical parameters for surrounding rock mass. The common software FLAC^{3D} is adopted to conduction the numerical analysis and the Mohr-Coulomb criterion considering tensile limit is chosen as the constitutive model for plug concrete and surrounding rock mass. The interface between plug concrete and surrounding rock mass is lower in strength compared to concrete and



(a) expanded wedge shape (b) straight column shape (c) curved column shape

Fig. 12 Deformation contours for different plug structures under check water level



(a) expanded wedge shape (b) straight column shape (c) curved column shape

Fig. 13 Axial stress components for different plug structures under check water level

rock mass so the interface element provided by FLAC^{3D} is introduced to simulate the contact behaviour of plug concrete and surrounding rock mass. Considering there is difference in the contact state of different locations around the plug, the contact is viewed void for the top arch area, which means the shear strength is set as zero in calculation.

4.4 Comparison of deformation characteristics for different types of plug

For straight column shape, curved column shape, and expanded wedge shape calculation scheme with the same calculation conditions, the deformation characteristics of surrounding rock mass, plug, and their interface are analysed as below and shown in Fig. 12.

The deformation characteristics of different types of plug have similar aspects, which are:

(1) the deformation of plug becomes gradually smaller from upstream to downstream along the tunnel axis direction;

(2) the maximum deformation of plug appears at its front surface where water pressure acts on and the difference of maximum deformation among different types of plug is not large;

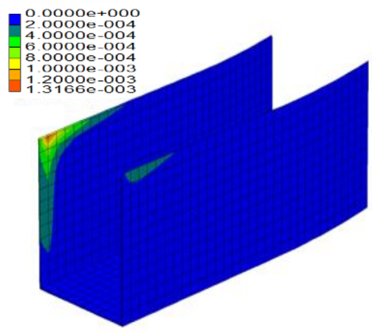
(3) from upstream to downstream direction, the impacting range of compressive deformation caused by water pressures accounts for about half of the plug length, and the deformation of the downstream part of plug is very small.

In addition, the deformation characteristics of different types plug also have different aspects, which are:

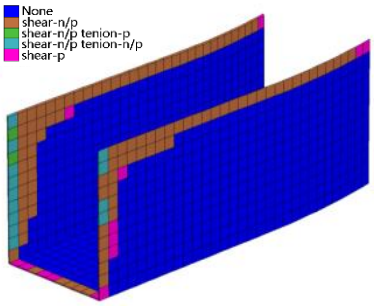
(1) the deformation of the straight column plug shows symmetrical distribution, and the deformation of the left and right sidewalls is roughly the same;

(2) the deformation of curved column plug shows asymmetric eccentric distribution, where the deformation of the outer sidewall is larger than the value of inner sidewall;

(3) the deformation distribution of expanded wedge-shaped plug has similar characteristics with straight column plug; their major difference is the impact of water pressure for the wedge-shaped plug is larger and causes surrounding rock mass generate larger outward deformation.



(a) Shear strain of interface



(b) Plastic zone of interface

Fig. 14 Calculation results of interface between lining concrete and surrounding rocks

4.5 Comparison of stress characteristics for different types of plug

A similar comparison is also conducted on the index of stress distribution characteristics.

When external water pressure is applied on the front face of plug structure, the principal compressive stress is about 1 MPa-2 MPa at the upstream surface of plug. The compressive stress becomes gradually smaller from upstream to downstream direction, as plotted in Fig. 13. Fig. 14 plots the mechanical response of interface between lining concrete and surrounding rock mass. Following aspects can be summarized by observing the results:

(1) the shear stress distributes unevenly along the interface: the front part has large shear stress ranging from 0.4 MPa to 0.6 MPa and the stress decreases gradually along the flow direction, with stress magnitude smaller than 0.05 MPa at the back part of plug;

(2) the shear stress decreases significantly within the front 20m part of the plug;

(3) the shear stress for wedge-shaped plug is smaller than other types of plug;

(4) the shear stress distribution characteristics of straight column plug and curved column plug are similar, while the shear stress of straight column plug is smaller than curved column plug.

4.6 Calculation of safety factor of plug structure based on overload method

The overload method is to gradually increase the imposed load while keeping the material parameters unchanged until the system reaches a critical state that instability will occur. The increased load multiple is called the load reserve safety factor. The characteristics of the plug under the overload condition are summarized as below.

(1) When the overload coefficient is small, the maximum deformation of different types of plug is not much different, the deformation increases with the increase of water pressure.

(2) The maximum shear strain and the plastic zone area of the interface of plug concrete and surrounding rock mass both increase with the increase of water pressure.

(3) With the increase of overload coefficient, the plastic zone of interface becomes almost completely interconnected, the deformation of the plug concrete and the maximum shear strain of the interface increase sharply, and the concrete structure of the plug has a significant deformation growth along the interface of plug concrete and surrounding rock mass.

(4) The ultimate bearing capacity of the plug is analysed by the calculation results of the overload method. The safe loads that can be withstood by the straight column, curved column and expanded wedge-shaped plugs are 6.0, 6.2, and 6.4 times of the water head corresponding to upstream checked water level, respectively.

By comparison, it is found that the overload safety factor of the straight column and curved column plugs is 94% and 97%, respectively, of the expanded wedge-shaped plug. The safety factor of the curved column plug is 97% of the expanded wedge plug, which is 1.03 times that of the straight column plug. This indicates that the curved column plug contains a certain "bending effect" and can provide a safety margin that is slightly larger than that of the expanded wedge-shaped plug.

4.7 Adaptability evaluation of the new plug structures

During the construction period and operation period of Wudongde hydropower plant, two upstream water level values are used to check the safety conditions of the new plug structures that are proposed for the project, respectively. The main calculation results are listed in Table 5. Judging from the obtained safety factors of different periods with various upstream water levels, the new plug structures for five diversion tunnels all meet the requirements of design codes, which requires a minimum safety factor of 3.0. The maximum deformation and shear stress of the plug structures are rational and in safe zone. Therefore, it is concluded that the proposed new plug structures are suitable and can be adopted in actual engineering practices.

Table 5 Main calculation results for the new plug structures at different periods

Water level / Calculation results	Construction period		Operation period	
	920.88 m	945 m	979.38 m	986.17 m
Maximum deformation of plug structures	0.30-0.75 mm	0.43-1.13 mm	0.6-1.60 mm	0.72-1.70 mm
Shear stress at the front of plug structures	0.3-0.4 MPa		0.4-0.6 MPa	
Safety factor of plugs for 1#~5# diversion tunnels	3.6-6.3	3.1-5.2	5.5-7.4	5.3-7.0

Moreover, it is worth noting that a concrete plug for sealing the diversion tunnel should be always placed at places with favorable rock mass condition to guarantee a sufficient bearing capacity. So the rock mass quality plays an important role. In this regard, if it is considered suitable to place a traditional plug structure, then a new plug structure can be also adopted.

5 Conclusions

(1) The traditional expanded wedge-shaped plug forms a “wedge clamping effect” by delivering water pressure to surrounding rock masses through its wedge shape, and makes the plug bear a considerable extent of external load. The anti-sliding capacity of the new curved column plug is supported by the inherent friction and cohesion of the interface of plug concrete and surrounding rock mass, the resistance produced by Poisson effect, and the additional resistance against sliding produced of bending effect.

(2) When the mechanical properties of the interface between plug concrete and surrounding rock mass are poor, the rank of safety margin of different types of plug from high to low is wedge-shaped plug, curved column plug and straight column plug. In this case, the safety margin of plug can be effectively improved by adopting the wedge-shaped plug. When the mechanical properties of interface are favorable, the column plug can provide the same safety margin as the traditional wedge-shaped plug. By adopting the column plug, the construction progress of plug can be accelerated and the surrounding rock mass will not be subjected to further excavation.

(3) The results of the geophysical exploration and tests show that the interfaces among lining, shotcrete, and surrounding rock mass of the plug section are in tight contact and well- cemented. There is no weak infillings and opening phenomenon of the contact interfaces. The recommended range of values for the shear strength of the interfaces among lining, shotcrete, and surrounding rock mass of the plug section are given. This laid a solid foundation for the use of column plugs for the diversion tunnel of Wudongde hydropower plant.

(4) Under the actual geological conditions and different work conditions of Wudongde diversion tunnels, the safety factor of the plug during the construction period is between 3.1 and 6.3, and the safety factor of the operation period is between 5.3 and 7.4, which is greater than the safety factor required by the design. It is therefore feasible to use a columnar type plug for the diversion tunnel Wudongde hydropower plant. At present, the proposed new type of plug structure has been reviewed by experts and will be formally implemented in the project.

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