Study of the mechanics of deformation and failure of a tunnel in red-bed soft rock

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Abstract: The red-bed soft rock formed in recent epoch is poorly cemented and has a high content of swelling clay minerals such as montmorillonite and illite. Its poor physical and mechanical properties cause many problems for engineering construction, especially for underground projects, sometimes even leading to serious project accidents. The properties of the red-bed soft rocks have been systemically studied both in China and abroad; these properties include the material composition, and the chemical and physical-mechanical properties. However, engineers and technicians tend to pay more attention to the mechanics of deformation and failure as well as to the treatment to such deformation and failure. Based on analysis of the geological environment and finite element numerical calculation for the Hui-Long-Gong Tunnel, this paper explains the mechanics of deforming failure resulting from the swelling of the red-bed soft rock through which the tunnel passes. Finally, suggestions for preventing deforming failure of such hydraulic tunnels are put forward.

Résumé: Pour la composition de matière de la roche meuble rouge, leur élément chimique et la caractère de physico-mécanique, l'étude systématique a l'avance dans le pays. Mais, Pour le mécanisme de sabotage de la déformation de l'éponte du tunnel meuble et son traitement sont un problème que les techniciens s'intéressent beaucoup. On a fait le calcul numérique de l'élément limité et l'analyse de l'environnement géologique du tunnel Huilongkon. Le texte a bien expliqué le mécanisme de sabotage de la déformation de l'éponte du tunnel de la roche rouge. Au cours de l'exécution du hydro-tunnel de telle roche, on a posé la proposition pour éviter la déformation de sabotage de l'éponte.

Keywords: Red-bed soft rock, Hydraulic tunnel, swelling rock, Process of the swelling of rock, Mechanics of deformation and failure of adjacent rock

INTRODUCTION

With the development of western China, more and more projects are constructed in the red-bed soft rock areas. Thus, more and more engineering geological problems are encountered during projects in such places. Due to their geologically relatively-young age, the rocks are poorly cement and have a high swelling clay mineral component such as montmorillonite and illite. The properties of the red-bed rocks are usually poor, which brings about many problems or even the large emergencies to construction of projects, especially underground projects in the red-bed soft rock area. The characteristics of red-bed soft rocks, such as the material composition, chemical content and physical-mechanical properties have been systematically researched both domestically and abroad and many achievements have been obtained. However, engineers and technicians pay more attention to the mechanics of deformation and failure as well as the treatment to such deformation and failure. Based on the geological environmental analysis and finite element numerical calculation of the Hui-Long-Gong hydraulic tunnel, this paper explains the mechanics of deforming failure resulting from the swelling of the red-bed soft tunnel's adjacent rock. Finally, recommendations for preventing deforming and failure of such hydraulic tunnel are presented at the end of this paper.

BRIEF DESCRIPTIONS OF THE GEOLOGICAL ENVIRONMENT OF THE TUNNEL

Basic geological conditions

Hui-Long-Gong (Palace of Dragon's return) hydraulic tunnel is located in Lang-Zhong county, Sichuan province, China, in the hill area of the north-west Sichuan geological basin. Structurally, it is at the north limit of the Ba-jiao-chang anticline of a hemicyclic tectonic system belonging to the rotational shear tectonic system of the middle of Sichuan. From the data of investigation and construction, the adjacent rock of the hydraulic tunnel is violet-red silty mudstone with the intercalation of greyish-white sandstone lens, the stratigraphic sequence of which belongs to the Peng-Lai group of upper series of the Cretaceous System. The attitude of the rock stratum through which the tunnel passes is of N55°E, with a dip of <1°. The rock mass of the hydraulic tunnel is intact.

The major physical and mechanical characteristics of the rock of the hydraulic tunnel

The mineral constitution, grain composition, dispersion degree, the parameter of the normal physics and characteristics of the swelling of the rock of the hydraulic tunnel have been tested, the results of which are shown in Tables 1 to 4 respectively.

Table 1. The X-ray silt crystals diffraction test results of the violet-red silty mudstone's clay-mineral component

Number of the samples	Percentage composition of the clay mineral（%）				
	illite	chlorite	quartz	feldspar	calcite
S0103	46	17	17	10	10
S0104	45	16	17	10	12

Table 2. The physical experimental results of the tunnel's silty mudstone

Number of the samples	Specific gravity	Free-swelling rate	Atterberg limits			Grain composition					Name of soil
						Method of test	Grain diameter mm			Dispersion degree	
			Wl	Wp	Ip		>0.05	05 ~0.005	<0.005		
		%	%								
1	2.74	35.0	31.2	17.8	13.4	With dispersant	16.0	49.5	34.5	96.2	Silty clay
2	2.74	36.0	31.8	17.0	14.8	Without dispersant	16.0	50.8	33.2		

Table 3. The routine physics mechanical index results of adjacent rock of the tunnel

Name of rock	Specific gravity	Natural density	Moisture content	Water – absorbing capacity	Porosity	Compressive strength		Softening coefficient
						Dry	Saturated	
		g/cm3	%			MPa		
Silty mudstone	2.69	2.38	2.96	6.03	14.0	23.2	14.8	0.45

Samples from the same horizon of the silty mudstone of rock of the tunnel and its results of swelling force are shown in Table 4.

Table 4. The test results of swelling force of silty mudstone

Number	Dry density	Pre -test		Degree of saturation after test	Swelling force
		Moisture content	Degree of saturation		
	g/cm3	%			MPa
5 1	2.165	7.56	75.0	100	0.292
5 2	2.326	4.47	64.9	92.8	0.101
5 3	2.376	5.51	91.9	96.3	0.073
5 4	2.243	6.91	81.4	88.3	0.055

Data from the tests above indicate the following characteristics of the adjacent rock of the hydraulic tunnel's silty mudstone:

The mineral composition of the hydraulic tunnel rock mainly comprised illite as well as chlorite. The percentage composition of illite and chlorite is 45~46% and 16~17% respectively, that is to say the total percentage composition of illite and chlorite is up to 61~63% of the mineral composition of the rock. The illite and chlorite occur as overlapped structure as the pages of a book; they are more hydrophilic minerals.

According to Yu Yilin (2001), the rock can be classified as normal swelling rock if the free-swelling rate of the rock is up to 25%; when the free-swelling rate of the rock is up to 30%, it can be classified as typical swelling rock. As shown in the tables above, the free-swelling rate is of 35.0~36.0%, which indicates that the hydraulic tunnel's rock belongs to a typical swelling rock.

- The swelling force of the silty mudstone, which increases as the saturation degree of the rock increases, is associated with the degree of saturation of the rock. As the degree of saturation of the rock increases up to 100%, the swelling force increases to the maximum value P_{max} = 0.292 MPa.

CHARACTERISTICS OF DEFORMATION OF THE TUNNEL'S SUPPORT

Brief description of the deformation and failure

Hui-Long-Gong tunnel is a 1156.6 m long aqueduct, the construction of which was started from 1987 and ended in April 1992. It started to transmit water in 1994. The support material of the tunnel's wall, bottom and most of the arch roof is strip-stone with mortar. A little part of the arch roof is supported with concrete. During the investigation of the tunnel after the flood period in 2002, it was found that the following deformations and failures occurred in many parts of the tunnel's support.

Many fractures distributed along the mortar between the strip-stone of the arch roof, even shear fractures occurred in some strip-stone of the arch roof and some of which was even broken into fragment and then dropped.

Some part of the walls began to swell towards the medial parts of the tunnel and there were many horizontal factures (with a maximum width of 30 mm) in the middle part of the walls. Some parts of the support of wall even collapsed

- The bottom swells upwards with the maximum height of 550 mm and the bottom is damaged severely, thus the water transmission is influenced seriously.

Grading of the deformation and failure

The following four grades of deformation and failure are defined based on the data from investigation and the quantitative deformation change in value and the degree of deformation and failure is estimated.

Grade I: There are almost no visible fissures in the support of the tunnel, but we can estimate some invisible mini fissures had been developed in the support; the degree of deformation is slight.

Grade II: The bottom swells upwards with a height of 100~200 mm, and the width of the fracture is 10~20 mm, which occurs in the mortar between strip-stone along the axis of the tunnel. There are almost no visible fissures in the support of the walls and arch-roof. The degree of deformation and failure is normal.

Grade III: The bottom swells upwards, with the height of swelling is up to 240~550 mm, and the width of the fracture is up to 40~50 mm, which leads to the strip-stone breaking away from the mortar. The walls swell towards the medial parts of the tunnel; the plumb-line deviation of the wall is 120~150 mm with the fractures developed at the height of 1.0~1.3 m of the wall. In this process there are some tensional and shear fractures occurring in the walls. The degree of deformation and failure is medial.

- Grade IV: The deformation and failure of bottom and walls is almost equivalent Grade III but there are more tension and shear fractures distributed in the support and in some part of the support there occurred breakdown. Some of the arch-roof is broken or crushed into fragments; therefore the entirety of the arch-roof is damaged, more or less, which leads to the loss of support of arc. The degree of deformation and failure is severe.

Table 5. The catalogue of grade of deformation and failure of tunnel's support

Distance along tunnel	0+000~0+250	0+250~0+314	0+314~0+588	0+588~0+871.5	0+871.5~1+071	1+071~1+155.6
Grade of deformation and failure	I	II	III	IV	III	I
Degree of deformation and failure	Slight	Normal	Medial	Severe	Medial	Slight

Table 5 shows that the severe deformation and failure segment is in the middle part of the tunnel; from this part to the direction of inlet or outlet there exist the medial, normal and slight deformation and failure respectively. It has been found that the sequence of deformation and failure of tunnel's support is as follows: firstly, the bottom began to swell upwards thus the fractures have been brought about; secondly, the middle part of wall began to swell towards the medial parts of the tunnel and in the same time started to crack; finally this process resulted in loss of support of abutment and fracture of the arch-roof.

Analysis on the mechanics of deformation and failure of the tunnel's support

Generally speaking, deformation and failure of the tunnel's support is due to the low strength of the materials comprising the support or the deformation and failure of adjacent rock. It is evident that we can rule out the former because if it was true, the degree of deformation and failure of the tunnel's support should be the same or equivalent. On the contrary, there is different degree of deformation and failure in the different sections of the tunnel as shown in Table 5. Therefore, we can infer that the deformation and failure of the tunnel's support is a result of the latter, that is, the deformation and failure of adjacent rock. There are also two types of pressures of adjacent rock that can bring about the deformation and failure of tunnel's support. First, the pressure from the wedge blocks which is originated from the weak discontinuities in the rock mass. Second, the pressure from deformation which occurred when the secondary stress induced during the excavation exceeds the yield strength of the adjacent rock. First of all, we must analyze the mechanics of the deformation and failure in order to decide what kind of measures are suitable for the remedial treatment of it. As for deformation and failure of Hui-Long-Gong tunnel, there two aspects to be considered:

- The tunnel is located in the Sichuan basin where tectonic activity is slight; hence the level of the ground stress is low, which rules out the deformation and deformation resulted from the high secondary stress.
- As shown above, the silty mudstone has the characteristics of swelling rock with the free swelling rate of 35.0~36.0% and the maximum value of swelling force Pmax = 0.292 Mpa. Therefore, it is suggested here that the deformation and failure are associated with the swelling of the rock.

THE SWELLING OF THE ROCK AND ITS IMPACT ON SUPPORT OF TUNNEL

Two type of swelling of the rock

As shown above, the mineral composition of the tunnel's silty mudstone is mainly comprised of illite ($K<1\ Al_2[(Si,Al)_4O_{10}(OH)_2.nH_2O]$), which has is structured like the pages of a book with strong hydroscopic properties. The swelling force mainly comes from the "wedging pressure" which brings about the process of void's absorption of water. The voids include pores and fractures in the rock. In the course of disintegrative tests on silty mudstone, it was found that there are two types of disintegration. One is the "wedging disintegration", the main process of which is as follows: when the sample of silty mudstone is put into water, it begins to crack and fractures can be noticed. With the further development, the sample disintegrates into fragments of different sizes. It is usually difficult for the fragments to disperse further, thus, the water is also usually clear. This type of disintegration is known as "wedging disintegration". The other type is "dispersive or swelling disintegration", the main process of which is as follows: when the sample is put into water, it begins to swell as the absorption of water goes on, then flaky fragments start to drop from the sample. As the fragments disperse into the water it becomes cloudy. The principal mineral of this type of rock is usually montmorillonite or illite. This is a different process of the swelling compared with the former.

There are pores and fractures in the tunnel rock. Pores are formed at the diagenetic stage. On the other hand, there are two types of fractures, one is tectonic or weathering fractures and the other is the blasting fractures formed during the course of excavation or the relaxation fractures in the relaxation sphere of tunnel. According to the data from the tests, the percentage of pores and fractures of silty mudstone of the tunnel is 14%.

It is the faces of the pores and fractures in the rock that form the interface of moisture and rock, which has high surface energy. When the interface is in contact with moisture, the interface absorbs the water strongly. The absorption of water at the interface leads to the reduction of surface energy. Some part of the reduction of surface energy changes into dissipated heat. The other part changes into the force, which is just the "wedging pressure" mentioned above. This type of force makes the interface of moisture and rock increase, which will bring about the swelling and disintegration. That leads to the higher swelling force. That is the process of the swelling of the rock.

The swelling force of adjacent rock and its impact on support of the tunnel

As mentioned above, Hui-Long-Gong tunnel is a tunnel for the transmission of water. The operational pattern of it is as follow: the tunnel transmits water from March to August, and from September to February of the following year, and then the transmission of water is stopped. As the transmission of water are mainly for irrigation, so the alternation of transmission of water and no transmission of water, including the alternation of different periods of time and alternation during the day, is very frequent. The alternation brings about cycles of wetting and drying which will certainly lead to frequent change of moisture content. As we know, the swelling of rock is associated with the change of humidity, so the operational pattern of Hui-Long-Gong tunnel provides external cause for the swelling. This will eventually make the rock up to its maximum value of swelling force, which leads to the deformation and failure of support of the tunnel. On the other hand, the change of humidity also leads to the swelling and the shrinkage of the rock, which is a reversible process. The repeated process brings about the swelling and the shrinkage of the rock. That is equivalent to the repeat force loaded on the support of the tunnel, which is another effect leading to the deformation and failure of support of the tunnel.

The free-swelling rate of the adjacent dark-red silt claystone is 35.0~36.0%, the swelling force, which increases as the degree of saturation of the rock grows, is associated with the degree of saturation of the rock. As the saturation degree of the rock is up to the 100%, the swelling force is up to 0.292Mpa. According to the data of S.L.Hvang etc., the maximum swelling value of the rock is relative to the humidity of the environment. The lateral restraint experimental results of S.L.Hvang etc, provide the equation of the maximum value of the rock as follows:

$$P_{max} = 0.0686RH - 0.008RH^2 + 1.473IRH + 0.0132IRH^2 - 0.0145RH \times IRH + 0.9594 \quad (1)$$

where:

P_{max} : the maximum swelling value of the rock;
RH: the relative humidity;
IRH: the index of relative humidity;

The equation mentioned above indicates that the swelling force is very sensitive to the change of the humidity as the maximum value and is direct ratio to the square of the index of relative humidity.

The process of the deformation and failure of support of the tunnel

The material of the tunnel lining is the strip-stone with mortar. Generally speaking, the thermal expansion property of stone and mortar is different. The change of temperature and humidity will bring about fissuring between the stone and mortar. The water or the moisture of environment will infiltrate into pores and fractures of the rock at the back of the support, which provide external condition for swelling of rock. Thus, the rock starts to swell, as the further swelling force loads back on the support the fissures between the stone and mortar will enlarge further. The infiltration of water or moisture into pores and fracture of the rock and the swelling of the rock will produce a step-by-step amplifying coupling effect on the support, which leads to the fractures and the failure developing further. On the other side, the tunnel is at a depth of 60~100 m with a maximum depth of 170 m at the middle part of the tunnel, which will induce a large gravity stress on the rock. As the silty mudstone is a soft rock with a saturated compressive strength of 14.8 MPa and a softening coefficient of 0.45. Under the large gravitational stress, the soft rock will suffer from creep deformation. The combination of swelling and creep deformation forms another step-by-step amplifying coupling effect, which is another effect resulting in the deformation and failure of support of the tunnel.

The numerical analysis of the deformation and failure

The calculation model was established to verify deformation and failure of the red-bed soft rock. During the analysis, the severe deformation and failure section, from 0+588 to 0+871.5, was selected as representative for calculation. The relaxation of the rock has been take into account and the thickness of the relaxed sphere is determined by analogue of the similarity, the value of which is about 3~5 m. Regarding the geological environment of the tunnel, the finite element calculation has been carried out under the gravitational stress field or under the gravitational stress and the swelling force field.

The results of the finite element calculation indicate the following:

Under the gravitational stress field, the higher deformation occurring at arch roof and walls, the displacement at the circumference of which is 140~160 mm, and the displacement at the circumference of the bottom, a little lower than that of the arch roof and walls, is 120 mm. Taking into account the softening and swelling with the swelling force of 0.292 MPa provided that at the range of 1 m of the circumference the degree of saturatation is 100%, it was found that the deformation of the rock increases, and maximum value is at the middle of the bottom, which is up to 200 mm. The displacement of the wall is up to 180 mm. The finite element calculation reveals that taking into account the softening and swelling, the calculated value of the deformation is equivalent to the observed values and the sequence of the deformation and failure also agree with that that occurs. This indicated that the deformation and failure of the adjacent rock is mainly resulted from the swelling of the rock with the change of humidity around of the rock.

CONCLUSIONS AND SUGGESTIONS

According to the mentioned mechanics of deformation and failure of the rock adjacent to the tumnnel, some conclusion and recommendation can be given below as a reference for the design and construction in similar projects.

The sealing and the supporting of the tunnel should be finished in time so as to reduce or avoid exposure of the rock, as well as the change of humidity. During construction of tunnel, the scheme of shallow hole and multi circulation excavation, especially the smooth blasting should be adopted. The groundwater and the discarded water should be drained well to avoid the immersion of rock from water.

The space of over-excavation should be backfilled with the non-swelling material such as boulders or rubble concrete; never use the rock ballast of the swelling source rock. That is because of the larger specific surface area of such material. Such material has a higher potential for swelling or swelling force than the source rock. So, it has a heavier impact on the support of the tunnel.

As the deformation and failure of support originate from the up-swelling of rock at the bottom (invert), so it is important to seal the rock with mortar in time. If necessary, anchoring can be taken into consideration. All such measures are adopted to prevent the bottom (invert) rock from swelling.

The materials comprising the support should be equivalent in their thermal expansion property. Materials with different thermal expansion properties such as strip stone with mortar should not be used to prevent cracking between the different materials.

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