Study on multi-arch tunnel leakage disease with influence of rainfall and groundwater change

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Abstract. It is known that the tunnel leakage is significantly affected by precipitation, for example the seasonal rainfall and the groundwater level change, which reduce the effective stress and the shear strength of the surrounding rocks, resulting in surrounding rock fracture and the connection of crack path between surrounding rock and lining structure. This paper reveals the relationships between the tunnel leakage with the lining crack width, the surface seepage, and the construction joints. Then the calculation equations of leakage water are deduced. According to the deduced equations, the influence of rainfall and groundwater level on leakage of the multi-arch tunnel is analysed. It is concluded that the leakage water increases with the rise of ground water level, decreases with the increase of the thickness of the lining; and the spot leakage and the surface leakage both increase as the increasing of the crack width and the seepage radius. On the basis of the conclusions, the preventions and treatment measures of leakage caused by rainfall and groundwater level change are put forward to ensure the long-term safe operation of the multi-arch tunnel.

1. Introduction

In mountainous areas, the separate tunnel or two separate tunnels are generally used when the conditions of hydrogeology and topography are suitable. However, consider some special terrain, such as steep terrain, discontinuous relief and the small mountain with short mileage, the separated tunnel is difficult to adapt, and the separate tunnel or two tunnels could lead to the overall highway alignment design not smooth, especially cause the project cost increases and the technical indicators fell at the same time. Given the above concern, the use of multi-arch tunnel has played a vital role, not only can reduce the overall cost of the project, but also adapt to the terrain, which can be connected with the route outside the tunnel smoothly, and also avoids dividing the route outside the tunnel, saves the project land, and cause less damage to the environment by the tunnel site. Therefore, the use of multi-arch tunnel has attracted many attentions, especially in recent years with the development of the transportation network, a large number of multi-arch tunnels have been constructed.

However, the leakage disease is the classic problem and found in most of the multi-arch tunnels. Due to the variability of partition wall forms in tunnel, the complexity of the hydrogeological conditions, the unreasonable waterproof and drainage construction and the defects of the tunnel
construction management itself, the leakage disease is a challenging task for designer [1], makes the multi-arch tunnel leakage problem become the highlight quality issue and subject to be solved in the underground engineering. According to the statistical analysis reported by the ministry of railways and the traffic department, 28.4 percent of China’s railway tunnels have serious leakage problem, and 30 percent for highway tunnels. Meanwhile, it is revealed that about 30 percent of underground railway tunnels in China’s cities of Beijing, Shanghai and Guangzhou suffer leakage problem. The application of highway multi-arch tunnel in China since the early 1990s, due to the construction scale of the traffic infrastructure expanding, China has become the country possesses the most quantity and mileage of multi-arch tunnel, and also the country suffers the most serious tunnel leakage disease, which need an immediate action.

Although the multi-arch tunnel is similar to the highway tunnel, it still has its own features. For instance, the leakage of partition wall is the most headache problem, and then is lining structure crack leakage. While there have been some literatures about the multi-arch tunnel leakage and its causes, a major current focus in the summary of this phenomenon [2-4], the mechanism of the disease and its relationship with the project construction process are rarely analysed. For highway tunnel, multi-arch tunnel is usually adapted to be multi-section tunnel, so that the asymmetrically-pressure and the weak-fractured surrounding rock are more likely to appear and easily affected by rainfall. There are many researches and summaries on the factors influencing leakage in multi-arch tunnel [5-9], but very a few on the mechanism of leakage caused by the rainfall and change of groundwater in the multi-arch tunnel, and this study will make some attempts.

2. Analysis of multi-arch tunnel leakage caused by rainfall and groundwater variation

In general, the multi-arch tunnel is shallow buried and usually in asymmetrically-pressure condition, so most of the rocks in the tunnel site are fractured and the joints and cracks are well developed, which provides a good storage space for rainfall infiltration. This feature will further influence the leakage of multi-arch tunnel. Due to the infiltration of rainwater along the slope, the strength parameters of rock and soil mass on the slope surface are greatly reduced, as the rain continues, the joints and cracks finally connected and the infiltration will form a hydraulic relationship with groundwater, cause the groundwater level to rise, that is, the water head under the multi-arch tunnel increases, lead to the leakage in the weak part of the multi-arch tunnel, like the lining cracks and the construction joints.

2.1. Seasonal rainfall

The seasonal rainfall influence is embodied in long-term cyclical infiltration, then the periodic weathering, precipitation and groundwater evaporation make the slope body on the multi-arch tunnel presents a dry-wet alternate condition, which lead to an obvious reduction of the effective stress and the shear strength. Suffering such a long-term process, the stress of surrounding rock will redistribute, which affect the deformation and the stability of the tunnel structure, especially once the groundwater has the chemical erosion effect, the occurrence of leakage disease chance is much greater.

The multiyear of seasonal rainfall makes the underground water level raise to a datum, this datum is likely to be below the tunnel and may not directly cause the tunnel leakage, but at this water level, the rock joints and fissures will easily form some connection with the tunnel site area and propagate the fragment, it is the fragmentation of the surrounding rock and variable fillings in the cracks that lead to the leakage of the fissure water and finally tunnel leakage disease occur. Moreover, the groundwater level is a value that changes dynamically over years, and fluctuates periodically above and below the tunnel, as shown in figure 1. Such repeated and ceaseless variation makes the broken surrounding rock mass in the alternating change of dry and wet, internal fracture more connected, especially the effect of corrosive groundwater is more prominent, and it is more likely to cause the leakage disease of the multi-arch tunnel.

Seasonal rainfall, periodic infiltration, rock and soil weathering, groundwater evaporation, etc., make the multi-arch tunnel slope body presents a dry-wet alternate condition, the effective stress is reduced, and the broken rock mass shear strength fell sharply. In such a long term process, the multi-
arch tunnel surrounding rock redistribution, affect the deformation and the stability of the tunnel lining structure.

Figure 1. Groundwater level changed of multi-arch tunnel caused by the rainfall

2.2. Extreme rainfall

Extreme rainfall itself is a kind of disaster, it induces the secondary disasters influenced the stability of the tunnel, such as landslides, mud-rock flow, etc., make the tunnel bear excessive deformation and uneven stress, and cause tunnel leakage finally. At the same time, the well propagated cracks in the surrounding rock and the fully supplied groundwater, which provide a favourable condition for the tunnel leakage.

In general, the site area of the multi-arch tunnel is a fissure zone, and this fissure area usually does not contain groundwater without rain supply, if extreme rainfall or water supply occurs, however, the problem will be quite serious, and during the construction of the multi-arch tunnel, sudden water gushing and mud bursting will be exposed. If the crack is not exposed and close to the tunnel, it will undermine the tunnel lining stiffness, and with the accumulation of time, periodical rain and varied groundwater, the fraction of surrounding rock gradually developed until connecting with the lining structure, which induce the damage of water proof system and drainage system in tunnel. Therefore, the rainfall is a striking feature on the tunnel leakage problem.

3. Calculation and analysis of water leakage in multi-arch tunnel

The groundwater level above the multi-arch tunnel is increased due to the replenishment of rainfall, when it reaches a stable level, the calculated water head is constant. According Dupuit assumption [10], the slope of the seepage free surface is very small when the groundwater flows slowly, that is, the water head \( H \) at the top of the multi-arch tunnel can be regarded as a constant, so the problem is simplified. As shown in figure 2, the velocity at point A is:

\[
    v_A = -k \frac{dh}{dx} = -k \sin \theta
\]

Figure 2. Assume that free surface is horizontal

As demonstrated in figure 2, the angle of free surface is very small, so replacing \( \sin \theta \) with \( \tan \theta \) is acceptable, the water flow is thus horizontal, and the multi-arch tunnel is under such hydrostatic pressure.
3.1. Calculation of lining crack leakage
For highway and railway tunnels in China, they have basically similar treatment for the external water load of lining structures, which are based on the engineering experience of hydraulic tunnels. According to the Chinese highway tunnel standard JTJ 026-90, the effect of external water pressure on concrete, reinforced concrete and prestressed concrete lining structure can be calculated by the following formula, called reduction coefficient method:

\[ P_c = \beta_e \gamma_w H \]  

Where, \( P_c \) is the pressure of groundwater acting on the surface of lining structure kN/m\(^3\). The groundwater pressure on the lining structure is generally not equal to the hydrostatic pressure formed by the groundwater column, so \( \beta_e \) is the reduction factor and the recommended value has been specified in the relevant code, which can be selected according to the actual project. \( \gamma_w \) is the weight of water kN/m\(^3\), and its value is 9.81 kN/m\(^3\). \( H \) is the acting water head of the underground water level to the center of the tunnel when the rainfall rises.

The inner surface of the multi-arch tunnel lining structure is exposed to air, which can be regarded as affected by a standard atmospheric pressure \( P_b \):

\[ P_b = 100 \text{Kpa} \]  

Then the pressure difference inside and outside the multi-arch tunnel lining structure is:

\[ P_c = \beta_e \gamma_w H - 100 \]  

For the cracks of lining concrete, the temperature stress of concrete, the uneven settlement of multi-arch tunnel and the defects during the construction are the leading cases. The formation of lining structure cracks provides a channel for groundwater seepage, rapidly rises the occurrence chance of tunnel leakage. Assuming that the concrete lining structure of a multi-arch tunnel has a permeability coefficient \( K_w \) before cracking, a permeability coefficient \( K_v \) after cracking, and a crack width of \( b \), therefore, the permeability coefficient \( K_v \) of the crack can be obtained by comparing the water flow in the crack with the pipe flow formula in hydraulics:

\[ K_v = \frac{gb^2}{12v} \]  

Where, \( v \) is the kinematic viscosity of water.

Therefore, the average permeability coefficient of concrete lining structure of multi-arch tunnel after cracking \( K \) is:

\[ K = K_w + b l K_v \]  

Where, \( l \) is the thickness of lining structure of multi-arch tunnel.

In general, the cracks in the multi-arch tunnel are not evenly open, thus the average of opening degree can be used and written as follows [11]:

\[ \bar{b} = \frac{\int_{b_{min}}^{b_{max}} b^3 f(b) \, db}{\int_{b_{min}}^{b_{max}} f(b) \, db} \]  

Where, \( f(b) \) is the distribution function of crack opening degree of multi-arch tunnel. Zeng, ect. have carried out track scanning measurement on it.

From the seepage principle, it can be known that the flow velocity \( V_b \) in the fracture is proportional to the hydraulic gradient \( J \) in the fracture:

\[ V = -K_v J \]  

Here, by substituting equation (6) into equation (8), the single-width velocity of water flow in the fracture can be obtained:

\[ V_1 = Vb = -(K_w + b l K_v)J \]  

According to hydraulics and seepage theory, the water flow in the fracture is similar to the flow between two parallel plates. According to Darcy’s law [12], the single wide discharge in the fracture is:

\[ q = bKJ \]
By dividing equation (4) by the lining thickness of the multi-arch tunnel, the water pressure gradient inside and outside the lining of the multi-arch tunnel at the crack was obtained, and substitute it into equation (10), the lining crack water seepage discharge per unit width is written as follow:

\[ q = bK(\beta\gamma wH - 100) \]  

(11)

Substitute equation (6) into equation (11), and obtain:

\[ q = b(K_w + \frac{b}{l}K_v)\frac{(\beta\gamma wH - 100)}{l} \]  

(12)

It can be observed from the equation (12) that the water leakage from the cracks in the multi-arch tunnel is mainly related to the crack opening degree, the discharge at the top of the tunnel, the permeability of the lining, the thickness of the lining and the hydrogeology condition around the tunnel site area.

Figure 3. Curves relation of crack single width runoff and groundwater

The equation (12) indicates that when the thickness of lining structure remains constant, the proportion of leakage of multi-arch tunnel and groundwater level is positive related, like shown in figure 3. With the increasing groundwater level and the width of the lining fraction, the seepage discharge will increase. Besides this, there is a very close relationship between the rise of groundwater level and rainfall in shallow buried and asymmetrical pressure multi-arch tunnels.

Figure 4. Curves relation of crack single width runoff and crack width

Assume that the groundwater level is at a constant value, it can be evaluated from figure 4 that the seepage amount of the multi-arch tunnel crack increases exponentially with the crack width. The larger the crack width is, the larger the flow rate of the single width is. Although increasing the thickness of the lining structure is beneficial to prevent leakage, it is not reasonable to increase the thickness blindly considering the reasons of economy and stress condition.
Assume that the thickness of the lining structure is constant, it can be identified from figure 5 that the amount of water leakage from the cracks of the multi-arch tunnel increases exponentially with the thickness of the lining structure decreases. The water leakage from the cracks of the multi-arch tunnel increases with the increase of the groundwater level also.

3.2. Calculation of spot and surface leakage

In order to analysis the water leakage at the spot and surface of the multi-arch tunnel, according to the geometric characteristics of leakage in the cracks of the lining structure, a square with unit length and width of b was selected in a crack section, like shown in figure 6, and it is equivalent to a circle with radius r:

\[ b \times 1 = \pi r^2 \]  

(13)

It can be seen when \( r \rightarrow 0 \), the circle becomes a point, that is, the spot leakage of the multi-arch tunnel. When r is greater than 0, the circle becomes a surface, that is, the surface leakage of the multi-arch tunnel. In operated multi-arch tunnel, it can be considered that the lining structure is waterproof, and the concrete permeability coefficient of the lining structure is very small and no leakage occurs, that is:

\[ K_w = 0 \]  

(14)

However, due to local corrosion of lining concrete, groundwater erosion and uneven stress, the leakage usually occurs like spot and surface leakage. Spot leakage is a circle with radius approaching 0, to make the calculation sample, the spot leakage is assumed to a unit circle with radius equal to 1. Then replace equations (13) and (14) into equations (12) to get the size of spot leakage:

\[ q = K_v \frac{\pi^2 (\beta e \gamma w H - 100)}{l^2} \]  

(15)

As shown in equation (15), the size of spot leakage is mainly related to the underground water level, the thickness of lining structure and the permeability coefficient of the local leakage point on lining concrete. Due to the difficulty in determining the permeability coefficient at the point of spot leakage, this study adopts the permeability coefficient calculated by RONG, C et al. [13]. \( K_v = 1.9 \times 10^{-6} \) cm/s, and the plot shown in figure 7.
Figure 7. Curves relation of spot seepage quantity and groundwater

Figure 7 demonstrates that the spot leakage quantity is proportional to the groundwater level. With the increase of the groundwater level, the volume of point leakage also increases, and with the increase of lining thickness, the amount of point leakage gradually decreases.

Figure 8. Curves relation of spot seepage quantity and lining thickness

Figure 8 indicates that the spot leakage quantity decreases with the increase of the thickness of the lining structure. If the thickness of the lining concrete is thick enough, the water amount of leakage basically approaches zero. However, due to the consideration of various factors, the thickness cannot be large enough in practice, and the leakage amount at the spot still tends to increase with groundwater level rising.

In another case, when the radius \( r \) is relatively larger, the surface leakage of the multi-arch tunnel occurs. And by substituting equations (13) and (14) into equations (15), the water leakage on the surface can be obtained:

\[
q = K_v \frac{\pi^2 r^4 (\beta \gamma_w H - 100)}{l^2}
\]

Equation 16 illustrates that the surface leakage is not only related to the water table, the thickness of lining structure and the permeability coefficient of surface infiltration, but also related to the surface infiltration area, that is, the leakage radius. In order to discuss the relationship between the leakage quantity and the surface infiltration radius, it is assumed that the lining thickness is 30cm, \( K_v = 1.9 \times 10^{-6} \text{cm/s} \), plot shown in figure 9:

Figure 9. Curves relation of spot seepage quantity and lining thickness
Figure 9 shows the leakage water quantity increases rapidly as the radius of the leakage surface increases. The larger the area of leakage, the larger the difference of leakage. When the local water level raises the leakage water quantity also increases. However, with the increase of lining thickness, the water leakage decreases gradually.

3.3. Calculation of water leakage in construction joint

Construction joint can be regarded as a special form of lining crack, but the difference is that the geometric form of construction joint is relatively regular, which is easy to calculate its area. However, the groundwater has a large flow loss along the way in the process of seepage, the change of hydraulic gradient is not clear, and the influence factors of permeability coefficient are various. The calculation formula for water leakage in construction joint is the same as that for crack leakage, but the difference is the value of permeability coefficient. Let the permeability coefficient be $K_f$, and then according to the calculation equation of lining crack, the calculation formula of water leakage in construction joint can be obtained as:

$$q = K_f \frac{(\beta e y_w H - 100)}{l^2}$$  \hspace{1cm} (17)

As indicated in equation 17, the water leakage of construction joints is mainly controlled by the groundwater level, lining thickness and the geometry of construction joints.

4. Countermeasures of leakage in multi-arch tunnel caused by rainfall and groundwater level change

4.1. Reasonable deformation joint of multi-arch tunnel

In order to adapt to the tunnel site area rainfall induced excessive deformation and displacement section, the tunnel structure integrity and the negative effect of deformation joint to tunnel itself, the essential principle is the combination design of rigid, flexible and waterproof. In detail, rigid means the setting of deformation joints should ensure a certain stiffness, which is conducive to the integrity and stability of the multi-arch tunnel. Flexibility means the setting of deformation joints makes it have corresponding flexibility, even if the multi-arch tunnel has a certain deformation and displacement capacity. Waterproof means the multi-arch tunnel deformation joint in addition to the rigid, flexible, but also has a certain waterproof effect, so as to reduce the multi-arch tunnel leakage disease.

4.2. Compatible multi-arch tunnel slope drainage system

In order to avoid the influence of rainfall on the tunnel structure and leakage disease, drainage system must be set on the slope of the multi-arch tunnel, including the tunnel slope surface drainage and the tunnel slope body drainage. This can ensure the promptly elimination or reduction of pore water pressure, reduce the long-term load of the supporting structure of the multi-arch tunnel, which is beneficial to limiting the occurrence of leakage diseases, and is conducive to the stability of the multi-arch tunnel. The tunnel slope surface drainage is mainly to block the water flow on the slope, reduce the surface infiltration of the slope surface, cut the length and depth of runoff caused by rainfall, and then alleviate the rainfall infiltration. For the rainfall discharge, setting up the side ditch, the slope top block ditch and platform block ditch are well accepted solutions. The reason of slope body drainage is mainly the groundwater converted from infiltration rainfall in the broken rock mass and the groundwater discharged from the deep layer. For such drainage problem, the main technique is to set up seepage ditch, blind ditch and inclined hole, etc. By applying above combination of slope surface drainage and slope body drainage in the multi-arch tunnel, the rainfall caused leakage problem can be greatly reduced.

4.3. Necessary multi-arch tunnel slope monitoring

Heavy rainfall induced excessive displacement and deformation of the multi-arch tunnel slope, which causes overburden soil stress redistribution and disturbs the stable surrounding rocks, resulting in the
lining structure crack, finally the water leakage occurs. Therefore, it is very necessary to monitor the slope body of the multi-arch tunnel, so as to adopt further measurement timely and avoid the large deformation and leakage disease caused by extreme rainfall. Especially the high risk multi-arch tunnel slope, a long-term tracking observation must be carried out.

5. Conclusion
1) The leakage of the multi-arch tunnel is significantly affected by temperature, seasonal rainfall and the variation of underground water level, which induces the alternately wet-dry change and the fracture connectivity of the surrounding rock. And it greatly reduces the effective stress of the surrounding rock and the shear strength, exacerbates the leakage disease of the multi-arch tunnel.

2) Based on the analysis of the influence of the rainfall, the expressions of the lining crack leakage, the spot leakage and the surface leakage of the multi-arch tunnel are derived. It is concluded that the leakage water volume, on the one hand, increases with the increase of groundwater level, the crack width and the surface infiltration; on the other hand, decreases with the increase of lining thickness.

3) Through the calculation and analysis of the leakage in multi-arch tunnel, some useful countermeasures are proposed. Mainly through the setting of deformation joint, the slope drainage system and the monitoring of the slope of the multi-arch tunnel, which can reduce the occurrence of leakage disease and ensure the long-term safety operation of multi-arch tunnel.

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