Study on analytical calculation method of water inflow in the tunnel of oblique crossing layered aquifer structure

Zhang Zhixiong¹, Liu Yang¹, Xu Mo², Zhang Yunhui³, Lin Yun⁴

¹. Chongqing Survey Institute, Chongqing, 401120, China;
². Chengdu University of Technology, Chengdu, Sichuan, 610000, China;
³. Southwest Jiaotong University, Chengdu, Sichuan, 610000, China;
⁴. Yunnan Urban and Rural Construction Investment Co., Ltd, Kunming, Yunnan, 650011, China
ckc@ahlctl.com

Abstract. Due to the complicated geological environment and karst hydrogeological conditions, water-inrush accidents often occur in the construction of tunnels in southwestern China. At present, there are many methods to predict tunnel water inflow, including analytic method and conventional hydrodynamic research method. There is a big discrepancy between calculated water inflow value and actual situation. Our research focused on the layered aquifer medium characteristics of water-bearing structure and movement characteristics. On the basis of existing tunnel gushing water inrush characteristics, the crossing relationships between tunnel and layered aquifer structure are divided into three categories, (I) tunnel longitudinal through layered aquifer structure, (II) tunnel through layered aquifer structure, and (III) tunnel obliquely crossing the layered aquifer structure. The revised formula of tunnel water inflow theory and experience in this study is inferred from steady-flow formula considering the boundary conditions. Inhomogeneous layered aquifer structure is considered as homogeneous structure, calculated by theory and experience formula. Next to the heterogeneity on one side of heterogeneity interface, the permeability coefficient of different strata can be fitted for a unified Kv; when crossing the layered water-bearing structure laterally, it is still calculated according to the original formula. When oblique crossing a layered water-bearing structure, the total flow rate is decomposed into two directions: transverse crossing and longitudinal crossing. The flow rates in the two directions are calculated respectively, and then superposed into the flow rates in oblique crossing.

1. Introduction

With the rapid growth of traffic line mileage in southwestern China, its construction and operation are restricted by complex geological environmental conditions and karst hydrogeological conditions and other factors [1]. According to the statistics of some long-buried tunnels built, the water inflow of tunnels in karst areas is large and hard to be predicted, and the risk of secondary disasters is severe. Analytical method, as a common method for forecasting water inflow, is widely used in engineering practice. Most tunnel survey and design stage in our country are the water inflow forecast. However, based on statistical results, the actual value has bigger error: About 75% of the statistical tunnels have a difference of more than 50% between the predicted value and the actual value, and only a few statistical tunnels have the actual value and estimated value within 20%, and the predicted value and
actual value of some tunnels have large errors, with a difference of dozens of times [2].

Actual tunnels intersect with tectonic line at a certain angle, and obliquely cross water-bearing structure. On the basis of conventional water dynamics method, many aquifers are infinite homogeneous formation, ignoring the influence of boundary conditions. The calculation of water inflow value is significantly distinguished from the actual situation. Therefore, this paper revised the semi-theoretical and semi-empirical formula of tunnel water inflow derived from steady flow formula considering the boundary conditions, using the principle of equivalent permeability coefficient. The revised results were verified by the actual tunnel finally.

2. Generalization of layered aquifer structure under crossing tunnel

The so-called layered aquifer structure refers to the geological structure composed of karst aquifer and clastic rock weakly permeable layer, which can store groundwater with a certain flow rule. The formation of the layered aquifer structure is mainly composed of three basic elements: (1) the strongly permeable rock layer, which is the main reservoir of the layered water-bearing structure; (2) The rock layer or rock mass with weak permeability has a relatively weak water storage capacity, and at the same time has a certain water isolation capacity, the water in the karst aquifer can be accumulated in large quantities;(3) The characteristics of free flow.

2.1. Characteristics of tunnel water inrush

This study collected the literatures of water inflow of crossing layered aquifer structure tunnels in last decade [3]. The tunnel project overview, geological conditions of tunnel site, crossing and water inrush characteristics have carried on the statistical analysis. Large-scale karst water and mud inrush disasters occur in multiple underground excavation construction, mostly of oblique crossing interface between soluble rock and insoluble rock. Water-inrush level and tunnel crossing relations are shown in table 1.

| Relationship between tunnel and structural line | Water gushing position | Characteristics of water inflow |
|-----------------------------------------------|------------------------|-------------------------------|
| Longitudinal cross                             | Exposing karst pipelines | a large amount of water inrush in the underground river pipeline, and the water inflow in other excavation parts is medium |
| Horizontal cross                               | Interface between soluble rock and non soluble rock | Large amount of water inrush and strong suddenness often form large-scale water and mud inrush disasters |
| Obliquely cross                                | Interface between soluble rock and non soluble rock | Large amount of water inrush and strong suddenness often form large-scale water and mud inrush disasters |

It can be seen from Table 1 that during the tunnel crossing, the most frequent and most serious water inrush disasters occur when the tunnel crosses the interface between soluble rock and insoluble rock. The water inflow characteristics are also different due to different cross relations between the tunnel and rock strata strike.

2.2. Generalization of layered aquifer structure

In southwestern China, a tunnel was actually often through complex geological structure. Different attitude of strata can form different boundary conditions. In this section, the crossing relationships
between tunnel and layered aquifer structure are divided into three categories when the strata dipping is steep: (I) tunnel longitudinal through layered aquifer structure, (II) tunnel through layered aquifer structure, and (III) tunnel obliquely crossing the layered aquifer structure.

2.2.1. **Longitudinal crossing layered aquifer structure**
Longitudinal crossing horizontal layered aquifer structure proposes tunnel extension direction is consistent with the formation strike. Tunnel construction generally does not pass through in this way, but such a passage structure can be formed in some tunneling sections.

The insoluble rock and compressional fault with relatively weak permeability is generalized into weak aquifer, which hinders groundwater movement. When water inrush occurs, the groundwater in the strong aquifer rapidly enters the tunnel and is almost dried out, while the groundwater in the weak aquifer slowly flows into the tunnel, as shown in Figure 1.

![Figure 1. Longitudinal crossing layered aquifer structure](image1)

2.2.2. **Horizontal crossing horizontal layered aquifer structure**
Horizontal crossing horizontal layered aquifer structure means that the extension direction of the tunnel is nearly perpendicular to the formation strike. This type of structure is relatively common in southwestern China, such as the barrier structure area in eastern Sichuan. Tunnels are mostly crossed in this way, especially through interbedded anticline or syncline. Soluble rock form strong aquifers store a large amount of groundwater; while insoluble rock form relatively water-proof layers reserves a small amount of groundwater, which also become relative water-proof boundaries (Figure 2).

![Figure 2. Horizontal crossing layered aquifer structure](image2)
2.2.3. Obliquely crossing the layered aquifer structure
In the process of the actual tunnel engineering construction in southwestern China, due to the complicated geological conditions, strata strike cannot always stay the same direction due to factors such as structure. So tunnel extended direction often assumes the angle intersect with the strike of the strata, namely tunnel oblique crossing the layered aquifer structure. This structure has the features both from the horizontal and longitudinal crossing layered aquifer structures.

![Obliquely crossing layered aquifer structure](image)

3. Calculated revision of water inrush flow using analytical method

3.1. Factors of predicting water inrush flow using analytical method

3.1.1. Influencing radius
Tunnel drainage caused by environmental disasters mainly occurs in roof drainage funnel range. Due to the tunnel length than width, crossing the layered aquifer structure, and differences of the formation permeability on both sides, "funnel" landing surface is shown as oval shape. Especially in the karst development of karst stratum, a huge anisotropic landing funnel is formed under the condition of a certain drainage. The axis of the radius is far greater than the short shaft radius along soluble rock strike, as shown in figure 4.

![Longitudinal crossing layered aquifer structure](image)

3.1.2. Drawdown of water level
Using analytical method to predict tunnel water inflow, the distance of the underground water level to the tunnel floor is regarded as maximum drawdown of tunnel water gushing. But for actual engineering tunnel with big buried depth, the calculated results would be lager if the method of the underground water level to the tunnel floor was conducted. Especially for smaller homogeneous medium permeability coefficient, water level drawdown generally does not reach the floor elevation. The calculation of maximum depth reduction is a difficult problem in theory and practice.

3.1.3. Permeability coefficient
Due to the irregular development of karst media, the selection of permeability coefficient is mainly based on exploration and hydrologic test data, combined with practical engineering experience to determine. Especially for areas with particularly complicated geological conditions, accurate geological judgment is often more reliable than purely relying on experimental calculation. The sensitivity of different water inflow formulas to permeability coefficient is also different.
3.2. Calculation revision for water inrush flow in different crossing modes
The formulas for the calculation of stable flow include Chobuyi formula, Kosyakov formula and Lahe-langmin formula, etc. Several assumptions should be set in the formulas for the calculation of stable flow:(1) the strata in the layered aquifer structure are homogeneous porous media;(2) The seepage conforms to Darcy’s law, that is, the seepage velocity in all directions is proportional to the hydraulic gradient;(3) The permeability coefficient of each stratum in the layered aquifer structure is the same in all directions.

The above various groundwater dynamics methods are based on the ideal model of infinite homogeneous aquifer. In layered aquifer structure, the strata are regarded as homogeneous aquifer. But the whole structure is inhomogeneous. In the calculation of dynamic formula, if a reasonable method was used, the anisotropic layered aquifer structure is transferred into homogenate one. Hence, the permeability coefficient is equal to the whole structure of the direction. Then the steady flow formula of water inflow in tunnel can be conducted to achieve more accurate results. Herein, the modes of (I) (II) and (III) discussed above are chosen for parameter correction and calculation of the water inflow.

3.2.1. Longitudinal crossing
There are two situations in which the influence radius of the tunnel is greater than or less than the distance between the tunnel and the heterogeneous surface. It is owing to the boundary conditions of the lateral groundwater recharge received by the tunnel are different.

When the influence radius of dredged groundwater in the tunnel is smaller than the boundary between the two strata, i.e., R<R1. The tunnel will not affect the groundwater in the weak permeable medium. Hence the semi-theoretical and semi-empirical formula derived from the stable flow can be directly used to calculate the tunnel water inflow.

However, when the influence radius of dredged groundwater in the tunnel is greater than that between the tunnel and the boundary of the two strata, i.e., R>R1. The boundary of the two strata can be regarded as the weak permeable boundary, and the morphology of the descending funnel changes. According to the commonly used influence radius calculation formula, namely Kusagin formula.

\[ R = 2S \sqrt{KH_0} \]  

It can be seen from Figure 5 that the influence radius in the strong aquifer is greater than that in the weak aquifer, and the factor determining the influence is the permeability coefficient K value. If the stable flow calculation formula is directly used to calculate the water inflow in the tunnel, a certain error will occur. Therefore, the permeability coefficient K value needs to be corrected and calculated.

![Figure 5. Seepage field of longitudinal crossing structure](image)

If the above heterogeneous structure is assumed to be a homogeneous aquifer with a permeability coefficient of Kᵥ, then the average permeability coefficient can be obtained.
Based on formulas (1) and (2), formula (3) can be achieved.

\[
K_v = \frac{R_1 + R_2}{K_1 + K_2}
\]

At this point, the influence radius of the side of the tunnel away from the heterogeneous interface can be obtained by Kucarkin formula, presented as formula (4).

\[
R = 2H \sqrt{K_v H}
\]

3.2.2. Horizontal crossing
Horizontal tunnel through layered aquifer structure, on both sides along the tunnel inlet direction and formation unlimited extension. So around the layered structure of layer can be considered as infinite homogeneous aquifer, as shown in figure 6. In this case, the water inflow calculation still adopts subsection solution method. The permeability coefficient across different strata are calculated based on semi-theoretical and semi-empirical formula of tunnel water inflow inferred by steady flow formula. Therefore, existing formula does not need to be corrected.

3.2.3. Oblique crossing
Oblique crossing is the most common situation in practical engineering, which means that the tunnel passes through the layered aquifer structure at a certain Angle. It is known by Darcy formula.

\[
Q = \omega V
\]

In the formula, the seepage velocity V is a vector. So the flow rate in the oblique crossing of the
tunnel can be decomposed into two directions: horizontal crossing and longitudinal crossing, as shown in figure. 7(a).

At this time, the tunnel can be equivalently decomposed into the flow during the horizontal crossing and the flow during the longitudinal crossing. The flow in the two directions can be calculated separately and then superposed into the flow during the oblique crossing. Supposing the tunnel passes through a layered water-bearing structure at an angle, two cases are discussed as below:

1) The total effective crossing length in the transverse direction is L\sin\alpha. The effective crossing length in the strong aquifer media with permeability coefficient K1 is L1. The effective crossing length in the weak aquifer media with permeability coefficient K2 is L2. The water inflow Q1 is calculated according to the model in the previous section of horizontal crossing through the layered aquifer structure, as shown in Fig. 7(b).

2) In the longitudinal direction, the different aquifer media permeability coefficient and break it down into two segments. If the first calculation through strong aquifer media of tunnel segment, it can be divided into an infinite number of sections along the formation strike direction, under the calculation of water inflow near the heterogeneous interface. Each section of the flow rate q is similar to longitudinal crossing layered aquifer structure calculation method in the previous section.

And then the classified infinite cross section of flow will be accumulated. The total flow of 1/4 elliptic cylinder with equal long and short axis can be obtained. The volume formula of different upper and bottom area of elliptic cylinder is list as below:

\[ V = \frac{1}{2} H \left( S_1 + S_2 \right) \]  

(6)
To simplify the calculation, the projection of the tunnel on the heterogeneous surface is approximately regarded as the height of the elliptic cylinder, as shown in Figure 8.

Taking the common formula of steady flow and Jupian theory as an example, the volume of water flow can be obtained using the algorithm of the volume of an elliptic cylinder with unequal top and bottom area.

\[ q_1 = \frac{1}{4} L \cos \vartheta \left[ (K_1 \frac{H^2 - h^2}{r_1 + r_2 - r} + K_2 \frac{H^2 - h^2}{R_2 - r}) \right] \]  

\[ r_1 = L \sin \vartheta \]  

\[ r_2 = 2(\frac{H - r_1}{r_1}) \]  

\[ \frac{1}{K_1} = \frac{1}{r_1} \left( \frac{1}{r_1} \frac{1}{r_1} \right) - \frac{1}{r_1} \frac{1}{r_1} \]  

\[ \frac{1}{K_2} = \frac{1}{r_2} \left( \frac{1}{r_2} \frac{1}{r_2} \right) - \frac{1}{r_2} \frac{1}{r_2} \]

The \( q_2 \) can be calculated in the same way.

However, the water inflow far away from both sides of the heterogeneous interface continues to be obtained according to the semi-theoretical and semi-empirical formula derived from the stable flow. Therefore, taking Jupian theory formula as an example, the total flow \( Q_2 \) is presented as below:

\[ Q_1 = \frac{1}{2} K_1 L_1 \cos \vartheta \frac{H^2 - h^2}{R_1 - r} + \frac{1}{2} K_2 L_2 \cos \vartheta \frac{H^2 - h^2}{R_2 - r} + \frac{1}{4} L_1 \cos \vartheta \left[ (K_1 \frac{H^2 - h^2}{r_1 + r_2 - r} + K_2 \frac{H^2 - h^2}{R_2 - r}) \right] + L_2 \cos \vartheta \left[ (K_2 \frac{H^2 - h^2}{r_1 + r_2 - r} + K_1 \frac{H^2 - h^2}{R_1 - r}) \right] \]

\[ Q = \sqrt{Q_1^2 + Q_2^2} \]

(4) The special case is, when \( L_1 \sin \alpha > R_1 \), namely \( \sin \alpha > R_1 / L_1 \), namely \( \sin \alpha > R_2 / L_2 \), \( Q \) should be divided into two parts. If \( L' = R_1 / \sin \alpha \), flow \( Q' \) larger than \( L' \) section is calculated with infinite mean value formula for the calculation of aquifer influx. The portion within \( L' \) length of flow \( Q \) with oblique crossing is corrected in the condition of oblique crossing layered aquifer structure. The sum volume of water inflow flow is equal to the sum of \( Q \) and \( Q' \).

The formula for \( Q_1 \) stays the same. But in the formula for \( Q_2 \), \( r_1 + r_2 \) becomes \( R_1 \), and \( r_3 + r_4 \) becomes \( R_2 \). Therefore, \( Q_2 \) formula obtained by the Choubouy formula is listed as below:

\[ Q_2 = \frac{3}{4} L_1 + \frac{1}{4} L_2 K_1 \cos \vartheta \frac{H^2 - h^2}{R_1 - r} + \frac{3}{4} L_2 + \frac{1}{4} L_1 K_2 \cos \vartheta \frac{H^2 - h^2}{R_2 - r} \]
4. Conclusion

(1) Layered aquifer structure is mainly composed of karst aquifer and clastic rock weakly permeable layer. The difference in permeability of water-bearing medium controls the occurrence and migration of groundwater, and forms different groundwater flow characteristics and circulation migration patterns.

(2) Based on the relationship between tunnel trending and layer aquifer strike, the crossing relationships between tunnel and layered aquifer structure are divided into three categories when the strata dipping is steep: (I) tunnel longitudinal through layered aquifer structure, (II) tunnel through layered aquifer structure, and (III) tunnel obliquely crossing the layered aquifer structure.

(3) In layered aquifer structure, each stratum is regarded as a homogeneous aquifer, but the whole structure is inhomogeneous. In the three kinds of tunnel crossing pattern, the inhomogeneous layered aquifer structure is transferred into homogenate. As such, the permeability coefficient is equal to the whole structure in the direction. We can apply the steady flow formula of water inflow in tunnel water inflow for more accurate calculation.

(4) Tunnel longitudinal crossing layered aquifer structure: Away from heterogeneity on one side of the interface, it is still needed to be carried out in accordance with the semi-experience and semi-theoretical formula calculation. And near the heterogeneity on one side of the interface, the permeability coefficient of different strata, based on the principle of subsection calculation, the permeability coefficient is fit for a unified Kv, making it can satisfy the formula of water inflow; Tunnel horizontal crossing layered aquifer structure: the water inflow calculation still adopts subsection solution method. The permeability coefficient across different strata is calculated based on the semi-theory and semi-experience derived from the steady flow formula. Then, the water inflow is calculated; Tunnel oblique crossing layered aquifer structure: the flow rate of tunnel oblique crossing is decomposed into two directions: horizontal crossing and longitudinal crossing. The flow rate of the two directions is calculated respectively and then superimposed into the flow rate of oblique crossing.

Reference

[1] Song, H.B. (2015) Hydrogeological conditions and route optimization of Xiaoyantang section of central Yunnan Water Diversion Project[D]. Chengdu University of Technology.
[2] Wang, Y.R. (2015) Analysis on improvement of karst tunnel water inflow calculation based on analytical method[D]. Chengdu University of Technology.
[3] Sun, J.Y., Zhang, Q. Xu, M. et al. (2011) Study on water inrush disaster and environmental impact of Tonghai tunnel construction[J]. Study on Soil and Water Conservation, 18(04): 69-73.
[4] Zhu, H.T. (2011) Characteristics of lining water pressure and Karst Treatment Technology of Qiuyueshan Tunnel[D]. Beijing Jiaotong University.
[5] Xu, H.X. (2010) Geological characteristics of Yesanguan Tunnel Construction and prevention and control of water inrush disaster[D]. China University of Geosciences (Beijing).
[6] Liu, J., Liu, D. Song, K. (2012) Evaluation of groundwater environment negative effect of Geleshan Tunnel Drainage on Chongqing Huaihua Railway[J]. Modern tunnel technology, 49(04): 178-183.
[7] Ying, L. (2014) Prediction of water inflow in huama tunnel[D]. Southwest Jiaotong University.
[8] Shen, F.X. (2017) Groundwater system in the north of Huaying Mountain and its influence on tunnel water inflow[D]. Southwest Petroleum University.