Calculation of drainage volume during tunnel construction based on the control of negative effects of ecosystem

Yu Wang, Yan Zhao, Xiaoyan Ge, Yongyu Li, Tianrong Huang and Qingming Zhang

ABSTRACT

Water inrush and seepage in tunnel engineering often lead to the loss of regional environmental groundwater resources and the imbalance of the hydrological ecological circulation system, which have a serious impact on the growth of natural vegetation. Based on the analysis of the burial depth of the critical water level of vegetation groundwater, a calculation method for the response of vegetation to water environment stress is established, and the water inrush and seepage volume of tunnel engineering under the condition of ecological balance protection are derived. By calculating the range and volume of the dewatering funnel when the tunnel underground water level reaches the maximum depth after water inrush and seepage, the maximum drainage value that must be controlled in tunnel construction is obtained. The proposed method has achieved certain practical results and could provide some theoretical reference for guiding the reasonable protection of groundwater, alleviating and eliminating adverse environmental geological effects in tunnel construction.

Key words | ecology, environment, groundwater, tunnel, vegetation

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HIGHLIGHTS

- The impacts of tunnel construction on an ecosystem can include chemical and biological impacts on the ecological functions and balance.
- For construction of the tunnel, the reasonable ecological water consumption can be calculated based on the above-mentioned water.
- In order to keep the groundwater level line above the burial depth of the critical water level of the root system, the drawdown of groundwater needs to be calculated.

INTRODUCTION

Mountain-crossing tunnels are usually constructed in complex and diverse groundwater environments, and changes in the groundwater environment will have a direct or indirect impact on the ecosystem and natural vegetation. As a kind of human activity, tunnel engineering often interferes to a certain extent with self-balance and self-circulation of regional groundwater, resulting in different environmental problems (Qumot 1990; Cherry 1998). For instance, lining seepage and long-term drainage in the tunnel often lead to exhaustion of groundwater, and subsequently, drops in the groundwater level, ground surface settlement and collapse, water source cut-off and so forth. In particular, the filling of the seepage channel in the surrounding rock will be gradually taken away by groundwater, which strengthens the channel connectivity and increases losses of water resources, causing damage to the local water environment of vegetation.

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Therefore, it is necessary to study the impact of tunnel engineering on the ecosystem and vegetation, adopt scientific and effective engineering techniques and plans, and evaluate the impact with scientific methods, so that coordinated development between the ecosystem, vegetation and tunnel engineering can be achieved.

METHODS

Impacts of tunnel engineering on the ecosystem

The impacts of tunnel construction on the ecosystem can be physical, chemical and biological impacts on the ecological functions and balance. As shown in Figure 1, disturbance and imbalance of the hydrologic system are the most obvious and typical embodiments of such impacts, and the degree of disturbance is closely related to the local groundwater content, round-robin manner of connectivity, geological conditions, precipitation, burial depth of the tunnel and construction methods of the tunnel engineering project.

Tunnel construction will inevitably affect the rock and soil structure and cause a stress-field redistribution and failure of the hydrologic round-robin system, changing the interaction mechanism and physical parameters of the material components, affecting the self-balance system of groundwater and resulting in ground surface settlement and collapse, water and soil loss and reduction of surface water, and so on. In areas with complex hydrogeological conditions or water-rich regions, inappropriate tunnel engineering methods (Wei 2009) will disturb the balance of regional water circulation, resulting in a larger range of the dewatering funnel and more ecosystem problems.

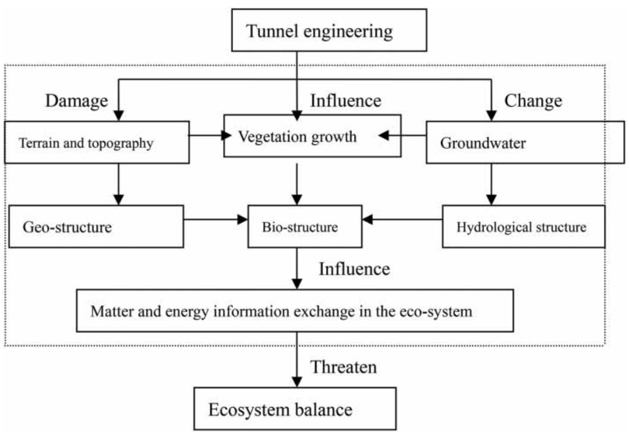

Figure 1 | Impact of tunnel engineering on the ecosystem and correlations between factors.

Research on water requirement of vegetation

In general, the growth and development of vegetation depends on specific soil conditions, climate conditions, groundwater environment and so on. Among them, the groundwater level has direct impact on the development of vegetation. For example, a plant will inevitably wither and fade when the groundwater level is lower than the critical water level of its root system (Voorti 2005).

As shown in Figure 2, the water inrush and seepage due to tunnel construction will cause groundwater level drops and formation of a dewatering funnel in the cave roof aquifer area, forming a new groundwater level line (namely the phreatic line) after groundwater stabilization at the end. After tunnel construction, in order to keep the groundwater level line above the burial depth of the critical water level of root system, the drawdown of groundwater and the range of the dewatering funnel need to be calculated, so as to guarantee the balance between the normal growth of vegetation

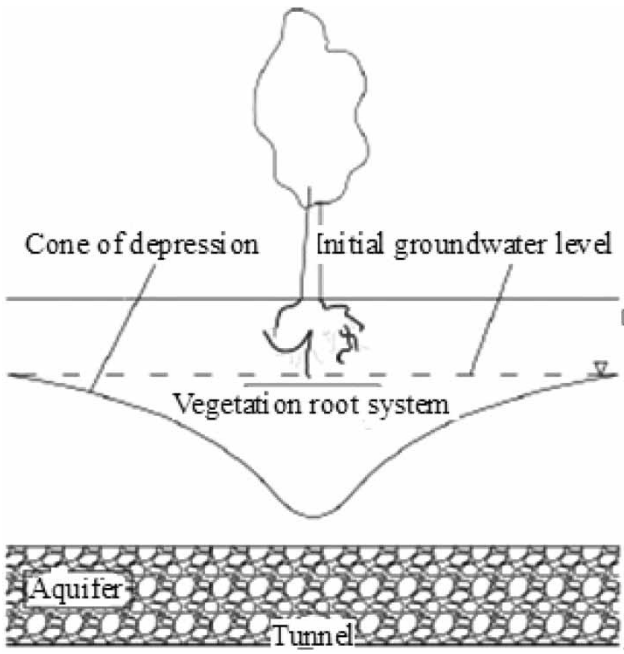

Figure 2 | Impact of tunnel engineering on the groundwater level.

and the regional ecosystem, thus controlling the maximum water yield of the tunnel.

There are three sources of vegetation water supply: (1) natural precipitation; (2) surface runoff and irrigation; (3) groundwater. The rise of capillary water can fully moisturize the soil or make the root system of vegetation directly reach phreatic aquifer when the water table is high, while the plants can grow for a long time.

The water requirement of natural vegetation and ecosystem in a specific region can be calculated on the basis of the amount of the phreatic loss, namely:

$$W = \sum W_i = \sum A_i \cdot \omega_{gi} \cdot K \quad (1)$$

where ω_{gi} is the amount of phreatic loss at a certain burial depth of groundwater level for vegetation type; K is the coefficients of vegetation, and A_i is the area of a certain vegetation type at a certain phreatic position.

The application range of formula 1 is based on groundwater level region. There is a nonlinear relationship between diving loss and plant water demand. Plant water requirements vary with the water level. When the water level is higher, the root system needs more water. When water levels are low, plant roots require less water. If the tunnel displaces more than the ecological carrying capacity, the plants will dehydrate and die.

During the design and construction of the tunnel, the reasonable ecological water consumption in the regional tunnel can be calculated based on the above-mentioned water usage method of vegetation and the ecosystem. Also, through investigation of the local hydrological conditions and precipitation, the water supply of vegetation that needs to be provided by the groundwater can be obtained; and then by back-calculation, the groundwater level required to support normal growth of vegetation can be achieved, which will be taken as the allowable drainage water volume of the tunnel to avoid damages on the ecosystem.

Calculation of water inrush during tunnel engineering

For the tunnel under the incomplete phreatic type of buried condition, the Sato method is usually employed to calculate the maximum water inrush q_0 per unit length, the normal water inrush q_s and the water inrush q_t at the moment t since the maximum water inrush begins to decay:

$$\mathrm{q}_{0-0} = \frac{2K\mathrm{m}\pi(H - \mathrm{r}_0)}{\ln\left[tg\frac{\pi(2H - 3\mathrm{r}_0)}{4h_0}\cot\frac{\pi r_0}{4h_0}\right]} \quad (2)$$

$$q_{s-0} = q_{0-0} - 0.584\varepsilon K r_0 \quad (3)$$

$$q_{t-0} = q_0 - \varepsilon\frac{K^2\mathrm{t}}{\lambda B}\cdot\frac{\mathrm{r}_0}{q_0}Kr_0 \quad (4)$$

where K is the permeability coefficient of the aquifer (m/d); H is the height from static water level to tunnel bottom (m); r_0 is the equivalent circle radius of the tunnel cross-section (m); m is the transformation coefficient, which is set at 0.86; h_c is the thickness of the aquifer (m); ε is the coefficient of experiment, which is set at 12.8; λ is the water-supply degree of the aquifer; B is the tunnel hole width before lining (m); t is the arbitrarily decreasing time between t_o and t_s (d); and $t_s = \frac{0.584\lambda B \mathrm{q}_0}{K^2\mathrm{r}_0}$.

The Ochiai Toshiro, Oshima Yuko and the empirical formula can be used to calculate the tunnel buried depth in the confined aquifer:

$$\mathrm{q}_{0-1} = \frac{2K\pi H - \mathrm{r}_0)m}{\ln[2(H - \mathrm{r}_0)/r_0]} \quad (5)$$

$$q_{0-2} = 0.0255 + 1.9224KH \quad (6)$$

$$\mathrm{q}_{s-2} = K\left[\frac{H^2 - \mathrm{h}_0^2}{R - B/2} + \frac{\pi H - \mathrm{h}_0)}{\ln[4R/B]}\right] \quad (7)$$

$$\mathrm{q}_{s-2} = KH(0.676 - 0.06K) \quad (8)$$

In the above formulae, R is the influencing radius of tunnel water inrush (m), and h_0 is the assumed depth of drainage ditch in tunnel cave (m).

The calculation of the maximum water inflow is controlled by many factors. The above empirical formula is also affected by the rock-soil water content, porosity, density and water permeability. In addition, tunnel drainage rate is also a key factor.

Calculation of the cone of depression in the tunnel

During tunnel engineering, the form of groundwater will gradually change with the drainage of groundwater, resulting in a drop in the water level and impacts on the hydraulic gradient and direction of motion. According to the related calculation methods of groundwater, the tunnel seepage can refer to the large-caliber pumping model, and using the well-point dewatering for analysis. After a certain period of constant flow pumping, there will be a cone of depression (Wilcox 2010). Based on the range and volume of the cone of depression and the average burial depth of vegetation groundwater, the allowable maximum drainage volume of the tunnel that satisfies the water requirement of vegetation can be obtained.

Due to the depth of vegetation groundwater balance, it will be affected by root ductility. According to the well point precipitation analysis, the funnel morphology has a close influence on the root depth.

Calculation of the range of the cone of depression

First of all, a clear understanding of the dewatering funnel area is helpful for defining the range of ecological effects. The dewatering funnel area in tunnel projects is always in the form of an inverted elliptic cone (Zhong-xin 2005). And the radial flow of non-standard inverted elliptic cone is similar to the radial flow of a standard inverted cone, which can be expressed by the ground influencing radius R of the cone of depression.

The radius of the dewatering funnel in the aquifer of the tunnel roof is:

$$R_0 = R + \frac{B}{2} \tag{9}$$

Based on the calculation model of the groundwater dewatering radius $R(t)$ under an unsteady flow state and the Theis equation, we obtain:

$$s = \frac{Q}{4T\pi} W(\phi) \tag{10}$$

$$\phi = \frac{r^2 \mu}{4Tt} \tag{11}$$

$$W\phi = \int_0^\infty \frac{e^{-y}}{y} dy = \phi - \ln\phi - \sum_2^\infty (-1)^n \frac{\phi^n}{n \cdot n!} - 0.58 \tag{12}$$

where r is the distance between the tunnel wall (mm); t is the seepage time (d); Q is the flow amount at the moment (t); s is the decline depth at a certain point in the pumping range at a certain time (d); T is the transmissivity coefficient; $W(\phi)$ is the well function; and μ is the coefficient of water storage.

The largest decline depth of ground influencing radius is generally considered to be 0 mm, namely $s = 0$ mm, and then:

For confined groundwater,

$$R = \frac{3(Tt)^{0.5}}{2\mu^{0.5}} \tag{13}$$

For phreatic groundwater,

$$R = \frac{3(h_c \mathrm{Kt})^{0.5}}{2\lambda^{0.5}} \tag{14}$$

where K is the permeability coefficient of the aquifer, λ is the water-supply degree of the aquifer; h_c is the depth of the drainage ditch in the tunnel cave (m).

This is the important basis for controlling the displacement of the tunnel based on the calculation model of the groundwater dewatering radius $R(t)$ under an unsteady flow state,

Since the water inrush time t in the tunnel is not long before constructing the lining, the ϕ will be larger at a larger distance r from the tunnel. Due to the limitation of the applicability of the above formulae, it is necessary to derive the Theis curve within the range of $0.001 \leq \phi \leq 1$ by the analytical method:

$$W(\phi) = 10.94\phi^{-0.066} - 10.86 \tag{15}$$

And the well function is:

$$W(\phi) = \int_0^\infty e^{-\phi} d\phi \tag{16}$$

The decline depth of water level:

$$s = (10.94\phi^{-0.66} - 10.86)\frac{q_t}{4T\pi} \tag{17}$$

For the ground influencing radius of the confined groundwater:

$$R = 2.15(\frac{Tt}{\phi})^{0.5} \tag{18}$$

For the ground influencing radius of the phreatic groundwater:

$$R = 2.15\left(\frac{h_c K t}{\lambda}\right)^{0.5} \tag{19}$$

According to the above formulae, the influencing radius is obtained, so that the boundary of the dewatering area can be drawn.

The long diameter of the longitudinal ellipse boundary of the tunnel is:

$$R_1 = 2R + L \tag{20}$$

The short diameter of the transverse ellipse boundary of the tunnel is:

$$R_2 = 2R + B \tag{21}$$

The calculation of the range of the descending funnel is based on the theoretical formula. Because of the discreteness of parameter acquisition, the radius of the funnel will be affected according to the local conditions.

Calculation of the volume of the cone of depression

The above analysis has clearly defined the range of the cone of depression. Based on this, using the geometric method to analyze the total volume of the cone of depression (V), the total water content in the dewatering area can be calculated to determine the allowable drainage amount of the tunnel. According to the geometric analysis, the volume of the dewatering funnel in the tunnel similar to the inverted cone can be calculated by the following formula:

$$V = \int_0^R 2\pi r s dr \tag{22}$$

Substitute the former formula $s = (10.94\phi^{-0.66} - 10.86)\frac{q_t}{4T\pi}$ and $\phi = \frac{r^2\mu}{4Tt}$ into the Formula (22), and we obtain:

$$V = 3.21\frac{q_t}{T}\left(\frac{Tt}{\mu}\right)^{0.066} R^{1.87} - 2.71\frac{q_t R}{T} \tag{23}$$

Consider the decline depth s_1 of the cave wall and the width B of the tunnel, we achieve:

$$V = 3.21\frac{q_t}{T}\left(\frac{Tt}{\mu}\right)^{0.066} R^{1.87} - 2.71\frac{q_t R}{T} + Bs_1 L \tag{24}$$

At this time, the average decline depth H of the water level within the drainage range is:

$$H = \frac{3V}{\pi R^2} \tag{25}$$

Finally, the total drainage limitation value Q of the groundwater is:

$$Q = V\mu \tag{26}$$

The above analysis can provide some accurate calculation results under certain conditions when the drainage amount is all provided by the raw storage capacity of groundwater in the surrounding rock, consuming the raw storage capacity all the time. The above calculation is particularly suitable for the dry season.

However, since the groundwater system is a complex and connective system, especially in the wet season, the water exchange between the funnel area and the outside regions is very frequent, and the supply increment brought by precipitation restrains the further development of the funnel to some extent (Donoho 1995; Scott 2013). It is necessary to ensure the moisture in the dry season to prevent ecosystem degradation for the water requirement of vegetation. Therefore, the above formulae can be used as an important reference for evaluation.

The numerical relationship between the volume calculation results of the funnel and the displacement of the tunnel is clear, but there is uncertainty caused by the diversity of water supply sources in the wet season and in the dry season.

Groundwater exchange between the tunnel area and the external environment

As the tunnel draining proceeds and the cone of depression develops, the groundwater in the wet season can be effectively supplemented by precipitation and ditch-water supply increment. Meanwhile, there will be declines in natural discharge such as the decrease of spring flow during the median water period and the dry season.

The drainage volume of the tunnel can be expressed as (Rao 2008):

$$Q_d = \mu A(\frac{\Delta h}{\Delta t}) + \Delta Q_r + \Delta Q_d \tag{27}$$

where Δh is the average precipitation level in the drainage affected area within the time period Δt; ΔQ_r is the supply increment during the tunnel drainage period, including the infiltration supply and seepage supply of the precipitation and surface water; ΔQ_d is the decrement of natural discharges during the tunnel drainage period, such as the decrease or cease of the overflow volume of spring water and the evaporation volume of phreatic water.

During the long-term drainage process of the tunnel, if the drainage amount of the tunnel is equal to the sum of the reduction of supply increment and excretion, that is (Zeng-Rong 2001):

$$Q_d = \Delta Q_r + \Delta Q_d \tag{28}$$

And then,

$$\mu A(\frac{\Delta h}{\Delta t}) \rightarrow 0 \tag{29}$$

There must exist: $\Delta h \rightarrow 0$.

At this moment, a new dynamic balance appears in the groundwater system of the surrounding rock of the tunnel: the drainage volume does not rely on the storage capacity any more, and thus the funnel area will not expand further and will gradually enter a stable state. Because some water supply is from spring water, which is a natural and directly usable form of groundwater, the decline or recession of the spring flow will lead to new conflicts in water supply and demand, and result in negative impacts on the environment. In other words, the stable state comes at a cost.

Project-based case study

Introduction to the project

The Huaying mountain tunnel is 4.69 km long. During the construction process, five serious water inrush events occurred in the western section of the tunnel, with a large volume of instantaneous water inrush and eruption of high-pressure water and mud flow, leading the project to be suspended for 69 days. To address this problem, the engineers redesigned the drainage scheme: the radius of the tunnel is set at 2,900 mm, the long draining hole is 1.3 km long, and the radius of the central water drainage pipe for joint drainage is 500 mm. The observation result shows that about 85% of water in the cave in the wet season and about 65% in the median water period and dry season can be drained. Although this scheme presents a remarkable drainage effect, there are still concerns that this will incur abrupt ecological imbalance.

The water inrush section of the Huaying mountain tunnel is about 1,175 m long and passes through the confined aquifer. The lithology mainly belongs to sandstone, siltstone and mudstone. The distance of the confined groundwater is $H = 239m$, the thickness of aquifer is $h_c = 478m$, the coefficient of permeability is $K = 0.0249m/d$, the coefficient of water storage is $\mu = 0.061$, the coefficient of transmissibility in the confined aquifer is $T = 19.05$, the equivalent circle radius of tunnel cross-section is $r_0 = 7.02m$, the tunnel hole width is $B = 12.4m$. The allowable maximum decline depth of tunnel that satisfies the water requirement from vegetation ($s_1 = 28.6m$) is calculated by the research on the regional ecosystem.

Calculation of water inrush

According to Formulae (2)–(4):

The maximum water inrush per unit length is: $q_{0-0} = 8.03m^3/d \cdot m$;

The normal water inrush is: $q_{s-0} = 6.51m^3/d \cdot m q_{t-0} = 7.99m^3/d \cdot m$. It can be found that time has little impact on the water inrush amount and volume, so we assume the groundwater level of the tunnel has reached the maximum decline depth $s_1 = 28.6m$ after $10d$ of excavation.

Then, according to Formulae (5)–(8):

$$q_{0-1} = 7.95m^3/d \cdot m \quad q_{0-2} = 12.41m^3/d \cdot m$$

$$q_{s-1} = 12.04m^3/d \cdot m \quad q_{s-2} = 5.17m^3/d \cdot m$$

Substitute the values of q_{0-1} and q_{0-2} into Formula (4), we obtain:

$$q_{t-1} = 7.93m^3/d \cdot m \quad q_{t-2} = 12.39m^3/d \cdot m$$

The composite average values are obtained:

$$q_0 = 9.48m^3/d \cdot m \quad q_s = 7.86m^3/d \cdot m \quad q_t = 9.45m^3/d \cdot m$$

Calculation of the cone of depression

According to Formulae (19)–(21), we obtain the dewatering radius ($R = 73.8m$), and thereby the long diameter of the top ellipse of the dewatering funnel ($R_1 = 1257.1m$) and the short diameter of the ellipse ($R_2 = 183m$). Due to the application range of Formula $\phi = \frac{r^2\mu}{4Tt}$ is $0.001 \le \phi \le 1$, the corresponding influencing range is $2.75m - 83.5m$, that is, the minimum applicable hole distance is $2.75m$ away from the tunnel hole wall, and the calculation width of the tunnel is $B = 12.4 + 2.75 \times 2 = 17.9m$. The volume of standard inverted cone ($V = 601759.32\text{m}^3$) can be obtained by Formulae (22)–(25).

The maximum allowable drainage volume of the tunnel

The result can be calculated by Formula (26):

$$Q = V\mu = 601759.32 \times 0.061 = 36707.30m^3$$

RESULTS AND DISCUSSION

Water inrush and vegetation destruction caused by tunnel engineering have an impact on the structure and functions of the ecosystem. Therefore, in tunnel engineering, we should turn from speed-oriented construction to environmentally friendly construction, resolve conflicts between the ecological carrying capacity and tunnel engineering, and thereby make tunnel engineering more eco-sustainable. Study on the impacts of tunnel engineering on the ecosystem can help understand the internal factors of ecosystem disturbance and imbalance and provide a theoretical basis for tunnel engineering to prevent or reduce its adverse effects on the environment.

CONCLUSIONS

Based on the theoretical methods of groundwater dynamics, we established a quantitative analysis method for the water inrush in tunnel construction and derived the calculation formulae for the volume of the cone of depression after water inrush and seepage. The allowable volume of water inrush and seepage that satisfies the water requirements of vegetation were obtained based on the hydrogeological parameters. The research result therefore can provide a basis for selection of methods to address groundwater-related problems in tunnel engineering.

The groundwater dynamics formulae are derived under certain assumptions, which may deviate from the actual conditions of the tunnel construction projects. In actual tunnel engineering projects, geological conditions and the vegetation are different as the location of the project differs, so it is advisable to adjust these formulae according to the local conditions.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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