

Retraction Notice

Title of retracted article: Numerical Simulation of the Influence of Tunnel Construction by Mining Method on the Seepage Field in Weathered Granite Stratum								
Author(s): Serges Mendomo Meye, Zhenzhong Shen								
* Corresponding author. Email: sergesmendomo@yahoo.fr								
Journal: Year: Volume: Number: Pages (from - to): DOI (to PDF): Paper ID at SCIRP: Article page:		Engineering 2020 12 6 424-456 https://doi.org/10.4236/eng.2020.126031 101185 https://www.scirp.org/journal/paperinformation.aspx?paperid=101185						
Retraction date:		2023-02-23						
Re \[\] X \[\]	traction initiative (multip All authors Some of the authors: Editor with hints from	 iple responses allowed; mark with X): O Journal owner (publisher) O Institution: O Reader: O Other: 						
	traction type (multiple re Unreliable findings O Lab error O Other: Irreproducible results Failure to disclose a may Unethical research	esponses allowed): O Inconsistent data jor competing interest likely to i	O Analytical error	O Biased interpretation or recommendations				
□ X □	Fraud O Data fabrication Plagiarism Copyright infringement	 ○ Fake publication □ Self plagiarism □ Other legal concern: 	O Other: □ Overlap	□ Redundant publication *				
	Editorial reasons O Handling error Other:	O Unreliable review(s)	O Decision error	O Other:				
Re X	sults of publication (on are still valid.	ly one response allowed):						

 \Box were found to be overall invalid.

Author's conduct (only one response allowed):

- X honest error
- $\hfill\square$ academic misconduct
- □ none (not applicable in this case e.g. in case of editorial reasons)
- * Also called duplicate or repetitive publication. Definition: "Publishing or attempting to publish substantially the same work more than once."



History Expression of Concern: U yes, date: yyyy-mm-dd X no

Correction: yes, date: yyyy-mm-dd X no

Comment:

The paper does not meet the standards of "Engineering".

This paper has been retracted to straighten the academic record. In making this decision the Editorial Board follows COPE's <u>Retraction Guidelines</u>. The aim is to promote the circulation of scientific research by offering an ideal research publication platform with due consideration of internationally accepted standards on publication ethics. The Editorial Board would like to extend its sincere apologies for any inconvenience this retraction may have caused.

Editor guiding this retraction: Prof. David L. Carroll (Editor-in-Chief of ENG)



Numerical Simulation of the Influence of Tunnel Construction by Mining Method on the Seepage Field in Weathered Granite Stratum

Serges Mendomo Meye^{1,2*}, Zhenzhong Shen^{1,2}

¹State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Manjing, China ²College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, China Email: *d2016010@hhu.edu.cn, *sergesmendomo@yahoo.fr

How to cite this paper: Meye, S.M. and Shen, Z.Z. (2020) Numerical Simulation of the Influence of Tunnel Construction by Mining Method on the Seepage Field in Weathered Granite Stratum. *Engineering*, **12**, 424-456.

https://doi.org/10.4236/eng.2020.126031

Received: February 14, 2020 **Accepted:** June 26, 2020 **Published:** June 29, 2020

Copyright © 2020 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Greative Commons Attribution International License (CC BY 4.0). http://creativecommons.org/licenses/by/4.0/ © ______ Open Access

Abstract

In actual space, considering the heterogeneity and anisotropy of rock and soil, the difference of hydrogeological conditions and the influence of tunnel excavation, tunnel seepage problem is a very complex three-dimensional seepage problem, which is very difficult to solve. The equivalent continuum model is one of the most commonly simplified models used in solving tunnel seepage problems. In this paper, the finite element software ABAQUS and the research results are used to establish a seepage numerical calculation model, study the influence of mining method construction on the seepage field in weathered granite, and clarify the influence of each stage of mining method construction on the groundwater environment. On this basis, the sensitivity of the seepage field to various factors such as natural environment, engineering geology and hydrogeology, tunnel construction and so on is analyzed, which provides a basis to establish the evaluation system of groundwater environment negative effect in weathered granite stratum by mining method tunnel construction.

Keywords

Seepage Field, ABAQUS, Weathered Granite, Mining Method

1. Introduction

Throughout tunnel construction, groundwater is usually discharged directly through the drainage system. Groundwater flows into the tunnel under the action of water pressure, resulting in adverse environmental effects, such as groundwater level drawdown and groundwater resource loss. The change of groundwater level depends on the relationship between groundwater recharge and discharge. Groundwater recharge is determined by local meteorological and hydrological conditions. Before the tunnel excavation, the groundwater recharge and discharge are in a dynamic equilibrium state, and the tunnel excavation increases the discharge of groundwater, which breaks the balance. Experience reveals that the mining method tunnel construction causes damage to the weathered granite surrounding rock and forms the excavation damaged zone (EDZ). The permeability of the surrounding rock in this area increases, resulting in an increase in the tunnel seepage flow and the negative effect of the groundwater environment.

Most tunnels are constructed in aquifers, and the tunnels under construction provide new drainage channels for groundwater. A large number of groundwater resources continue to drain through tunnels, resulting in a certain range of groundwater level decline, subsequent in drying up of the surface water system and deteriorating the ecological environment. With the enhancement of people's awareness of environmental protection and the further improvement of environmental defense requirements, the negative impact of tunnel construction on the environment has gradually become the focus of attention. At the same time, a series of research results on the impact of tunnel construction on the groundwater environment has emerged.

Li et al. [1] studied the influence of runnel construction on groundwater level and chemical composition in Matsumoto City, Japan. Based on the variation law of groundwater level and chemical composition, they analyzed the influence of tunnel construction on the hydrogeological environment. The results showed that the drainage of tunnel construction resulted in the drying up of some springs, which resulted in the dramatic reduction of river flow. Lipponen [2] analyzed the influence of Päijänne tunnel construction on local groundwater environment by using Geographic Information System (GIS), identified dangerous reas and critical dangerous areas, described the expansion of dangerous areas by using surface subsidence and aerial survey data, pointed out the causes of surrounding rock pressure in the reinforcement circle of larger tunnels, and gave the least advantage position and possible dynamic head. Chae et al. [3] investigated a large number of metro tunnels in Seoul, South Korea. The results showed that the average annual water inflow was 6.3×10^7 m³, which caused a serious decline in the local groundwater level. Vincenzi et al. [4] studied the negative environmental effects of the construction of the Italian Firezuola Extra Long Tunnel. The results showed that the drainage of the tunnel caused serious damage to the surrounding ecological environment, resulting in the depletion of a large number of surface water and springs. The construction of a rock mass tunnel in Northwest Spain has caused a significant drawdown in the groundwater level, which has seriously affected the production and life of nearby residents. Raposo et al. [5] based on field monitoring data using groundwater balance model, analyzed the present situation of groundwater environment, optimized tunnel construction methods and waterproof and drainage measures, and re-evaluated groundwater recharge, through a series of control measures to reduce the impact of the tunnel on the groundwater environment. Liu *et al.* [3] [4] made a thorough and systematic study on the interaction mechanism and control technology between tunnel and groundwater environment in the fractured rock mass. Taking Dongkeling Tunnel of Guizhou-Guangzhou High-speed Railway as the engineering background, Wang [6] studied the influence of WellPoint precipitation on the groundwater environment and the influence of the construction of water-rich soft rock tunnel on groundwater environment and tunnel stability. Yuan [7] studied the negative environmental effects during the construction stage of the Wushaoling railway long tunnel and analyzed the influence of tunnel construction on the environment and its inducing factors. Wang *et al.* [8] considering the effects of rainfall recharge, real three-dimensional topography, tunnel burial depth and space-time excavation on tunnel water inflow, his paper used GIS and FLAC3D to analyze the water inflow and its impact on groundwater level in Shinkansen Tunnel in Kyushu, Japan.

According to the above literature review and analysis, a lot of research has been carried out on the interaction between tunnel engineering and groundwater environment. However, most of the research results are applicable to Karst tunnels, and there is still a lack of in-depth study on the influence of mining method tunnel construction in the water rich weathered granite stratum. In this paper, considering the effect of excavation damaged zone, the influence of tunnel construction with mining method in weathered granite on seepage field is studied by numerical simulation using the finite element software ABAQUS. The variations of water inflow into tunnel, groundwater level, pore pressure, and velocity of groundwater in different stages of tunnel construction are determined, and the sensitivities of seepage field to a range of influencing factors during tunnel construction are analyzed.

2. Material and Methods 2.1. Computing Method

The solution of the seepage problem is to solve the basic differential equation of seepage under the condition of the known definite solution, so as to obtain the head distribution and seepage flow of each point in the seepage area. Due to the complexity of medium parameters, geometry and boundary conditions, most analytical formulas are limited in application. With the rapid development of computer technology and numerical calculation methods, more effective methods are provided for solving complex seepage problems. The finite element method is one of the most widely used numerical methods today, which can be applied to any physical field described by the differential equation. The basic steps of solving seepage problems by the finite element method are as follows: 1) define the seepage analysis domain. The actual seepage problem is generalized, and the relevant geometric and physical parameters are given; 2) discrete seepage analysis domain. In this paper, the seepage analysis domain is meshed and



divided into a collection of finite elements; 3) select the appropriate type function. The distribution law of water head in the element is represented by the appropriate type function, and then the water head at any point in the seepage analysis domain is represented by the node water head of the element; 4) the control equation of the element is established. The control equation of the element is established by the variational method or the weighted residual method; 5) establish the whole control equation. The control equations of all elements are assembled and the finite element equations are established; 6) solution. Combined with the condition of a definite solution, the whole control equation is solved, the value of the water head of all nodes is obtained, and then the whole seepage problem is solved.

2.2. Computational Model and Parameters

The tunnel section in the numerical calculation model is based on a standard composite lining section of grade IV surrounding rock of the metro tunnel in the study area, as shown in Figure 1. The tunnel section is excavated by two steps. The initial support adopts C25 concrete with a thickness of 150 mm, the second lining adopts C40 reinforced concrete, and the arch wall is 300 mm thick.

The design of waterproof and drainage system for metro tunnels comprehensively considers engineering geology, hydrogeology, structural characteristics, and construction methods, and obeys the principles of "Giving priority to prevention, balancing hardness with the softness (flexibility), multiple lines of defense, adopting measures to local conditions and comprehensively managing". Mainly structural waterproof, construction joint and deformation joint



C25 shotcrete. P6 impervious grade.

Waterproof layer (Non-woven fabrics and PVC waterproof board). applied to whole section. C40 moulded reinforced concrete. P10 impervious grade.

waterproof, supplemented by additional waterproof layer to strengthen waterproof. The tunnel waterproof and drainage system are shown in **Figure 2**. The first waterproof curtain is formed by systematic grouting for the initial support. The impermeability grade of Shotcrete for the initial support is P6, and the impermeability grade of P10 concrete is used for the secondary lining. Geotextile and waterproof boards shall be laid between the primary support and secondary lining of the tunnel, and the whole section shall be arranged. The longitudinal and circumferential construction joints of the tunnel adopt the secondary waterproof measures of galvanized steel sheet waterproof belt + waterproof membrane layer (PVC waterproof board with external waterproof belt). The deformation joints adopt the composite waterproof measures of external waterproof belt + stainless steel edge rubber waterproof belt + backwater surface layer + stainless steel water connection channel.

Based on the geological model of the tunnel section shown in **Figure 3(a)**, the tunnel seepage numerical calculation model is established by using the finite element methods software ABAQUS, as shown in **Figure 3(b)**. The model is 200 m high and 500 m wide. The initial groundwater level is 40 m above the vault. The coordinate origin is located at the midpoint of the ground line. The calculation model includes three weathered granite strata: strong, medium and micro. The tunnel is located in the weathered granite stratum. Referring to the results of the in-situ wave velocity test, the thickness of EDZ is 1.5 m. In view of the water-resistant layer impermeability effect, the computation model is simplified to a certain extent without simulating the influence of backfill concrete at the bottom of the tunnel on the seepage field.







Figure 3. Tunnel geological model and seepage numerical calculation model. (a) Geological model; (b) Seepage numerical calculation model.

The model material includes surrounding rock, EDZ, grouting circle, shotcrete and secondary lining (including waterproof layer). The Mohr-coulomb constitutive model is used for surrounding rock, EDZ, grouting circle, and shotcrete, and the elastic constitutive model is used for lining. According to the geotechnical engineering investigation data, the later supplementary test and the related theoretical calculation in the study area, the physical and mechanical parameters of the materials are determined as shown in Table 1. Among them, k is the permeability coefficient, ρ is the density, c is the cohesion, on, ø is the friction angle, E is the elastic modulus, and μ is Poisson's ratio. Four-node plane strain pore pressure solid element (CPE4P) is used for meshing.

2.3. Analytical Step and Boundary Conditions

In the study area, the IV-grade surrounding rock of the tunnel is constructed by the two-step method. Combined with the actual construction situation, the following analysis steps are established: (1) *in-situ* stress balance; (2) excavation of the upper step (1 d); (3) support of the upper step (5 d); (4) excavation of the lower step (1 d); (5) support of the lower step (5 d); (6) inverted arch excavation (1 d); (7) inverted arch support (2 d); (8) inverted arch lining and backfill (20 d); (9) arch wall lining (3 a). The time of step (9) is set to 3 a in order to investigate the long-term variations of the groundwater environment after completion of the construction. Tunnel excavation, support, and lining are simulated



Material	k/(m/d)	$\rho/(kg/m^3)$	c/kPa	<i>φ</i> / °	E/GPa	μ
Strongly weathered granite	1.60	2000	60	22.8	1.2	0.3
Moderately weathered granite	0.70	2500	500	35	5	0.25
Micro-weathered granite	0.02	2700	1500	45	15	0.2
Excavation damaged zone	4.20	2300	430	32	4.3	0.25
Grouting circle	0.07	2600	600	40	6	0.25
Shotcrete	1e-5	2400	2800	50	28	0.2
The secondary lining	0	2500	1	1	32 .5	0.2

Table 1. Physical and mechanical parameters of materials.

by life and death elements, while the simulation of EDZ and subsequent grouting circle is realized by controlling the material properties of asynchronous analysis by field variables. In order to be more in line with the actual situation, transient analysis is used in the first eight steps (1 - 8), and steady-state analysis is used in step (9).

The mechanical boundary conditions of the model are: constraining the horizontal displacement of the left and right boundary, constraining the horizontal and vertical displacement of the bottom boundary. The model seepage boundary conditions are: the pore water pressure on the left and right boundary is fixed, the head boundary is fixed, and the bottom is an impervious boundary. After tunnel excavation, the boundary of the tunnel is free drainage. After shotcrete, the inner boundary of the concrete is free drainage. After the secondary lining, the inner boundary of the lining is an impermeable boundary. The pore water pressure at the free drainage boundary is set to 0.

3. Results and Discussions

3.1. Variation Law of Seepage Field in Mining Method Construction Process

3.11. Variation Law of Tunnel Seepage Flow

The seepage flow of the tunnel directly reflects the loss of groundwater resources caused by tunnel construction. Through laying flow monitoring nodes on the drainage surface of each construction stage, the sum of seepage flow of all nodes on the drainage surface is calculated, and the tunnel seepage flow in each construction stage is obtained, so as to grasp the law of groundwater resources loss in the construction process. Figure 4 depicts the seepage distribution of drainage surface joints in each stage mining method tunnel construction in weathered granite. The seepage flow of all joints on the drainage surface is summed and the seepage flow value of the tunnel is obtained. Figure 5 is the average seepage flow chart of the tunnel in each construction stage. The abscissa coordinates 1 - 8 in the figure represent the different stages of the two-step construction method. The sequence is the excavation of the upper step, the support of the lower step.





Figure 4. Seepage distribution chart of drainage surface joints in each construction stage (m^3/s) . (a) Upper step excavation (t = 1 d); (b) Supporting of upper steps (t = 6 d); (c) Excavation of lower steps (t = 7 d); (d) Lower step support (t = 12 d); (e) Inverted arch excavation (t = 13 d); (f) Inverted arch support (t = 15 d); (g)Inverted archlining (t = 35 d); (h) Arch wall lining (t = 3 a).

and the excavation of the inverted arch, invert support, invert lining, and arch wall lining.

From Figure 4(a) and Figure 4(b), when the excavation of the upper step is completed (t = 1 d), groundwater flows into the tunnel through the tunnel



Figure 5. Average daily seepage flow chart of tunnels in different construction stages.

excavation face, the maximum node flow $RVF_{max} = 5.069e^{-5} \text{ m}^3/\text{s}$ is located at the arch foot of the excavation face. After the initial support of the upper step is completed (t = 6 d), because the permeability of the shotcrete is much lower than that of surrounding rock, groundwater flows mainly through the excavation bottom. At this time, the maximum node flow $RVF_{max} = 8.933e^{-5} \text{ m}^3/\text{s}$ is located at the junction of the initial support and the excavation bottom.

From **Figure 4(c)** and **Figure 4(d)**, when the next step excavation is completed (t = 7 d), groundwater flows into the tunnel from both sides and bottom of the lower step. The maximum node flow $RVF_{max} = 4.465e^{-5}$ m³/s is located at the junction of the initial support of the upper step and the excavation surface of the lower step.

After the completion of the lower step support (t = 12 d), the groundwater behind the initial support of the upper and lower steps flows along with the initial support directly to the excavation bottom. At this time, the node flow at the junction of the initial support of the lower step and the excavation bottom is the largest, and $RVF_{max} = 9.105e^{-5}$ m³/s.

From Figure 4(e) and Figure 4(f), when the inverted arch excavation is completed (t = 13 d), groundwater flows mainly through the arch bottom. The node with the largest flow is located at the junction of the lower steps and the arch bottom, and $RVF_{max} = 5.252e^{-5}$ m³/s. After the inverted arch support is completed (t = 15 d), the initial support is sealed into a circle, the groundwater infiltrates from the initial support, and the discharge of drainage surface nodes decreases significantly, $RVF_{max} = 6.767e^{-5}$ m³/s.

From **Figure 4(g)** and **Figure 4(h)**, when the secondary lining of inverted arch is completed (t = 35 d), groundwater cannot flow through the bottom of the arch due to the impermeability effect of the waterproof board, and can only infiltrate through the initial support of the upper and lower steps. At this time, the maximum node flow is $RVF_{max} = 8.672e^{-5}$ m³/s. With the completion of the second lining of the arch wall, the second lining is sealed into a circle. Without leakage of the waterproof board, the flow of all nodes in the tunnel is 0 m³/s, and the seepage flow of the tunnel is 0 m³/s.



As shown in **Figure 5**, the daily average seepage flow of tunnels in each construction stage is as follows: ① upper step excavation $(70.42 \text{ m}^3/\text{d}) > ③$ lower step excavation $(48.74 \text{ m}^3/\text{d}) >$ inverted arch excavation $(40.72 \text{ m}^3/\text{d}) > ②$ upper step support $(38.80 \text{ m}^3/\text{d}) > ④$ lower step support $(32.54 \text{ m}^3/\text{d}) > ⑥$ inverted arch support $(0.03 \text{ m}^3/\text{d}) > ⑦$ inverted arch lining $(0.03 \text{ m}^3/\text{d}) \otimes$ arch wall lining $(0 \text{ m}^3/\text{d})$. With the progress of construction, the daily average seepage flow of the tunnel reveals a tendency of fluctuation and decrease. At each excavation stage, the seepage flow will take place in different degrees of step, and with the completion of the corresponding initial support, it will fallback. The loss of groundwater resources caused by the mining method mainly occurs in the construction stage before the initial support closing. After the initial support closing, the daily average seepage flow of the tunnel decreases by $0.03 \text{ m}^3/\text{d}$. Since then, the influence of tunnel construction on the groundwater environment has been very small.

3.1.2. Variation Law of Groundwater Level

The variation of groundwater level is one of the important bases for evaluating the influence of tunnel construction on the groundwater environment. Figure 6 depicts the distribution of groundwater levels in different stages of mining method tunnel construction in weathered granite. S_{max} is the maximum water level drawdown, and t represents the time. According to Figure 6, the lowest groundwater level during construction is located directly above the tunnel vault. Figure 7 depicts the curve of the minimum groundwater level with time during the construction process. (1) - (8) in the figure is each stage of the two-step method construction, which is consistent with Figure 5.

Based on the analysis of Figure 6 and Figure 7, it can be concluded that the groundwater level continues to decline before the completion of the inverted arch support during the construction stage, and the lowest groundwater level during the whole construction process is -22.62 m, which appears after the inverted arch excavation.

The lowest water level in the first five construction stages and the daily average decline frequency are fixed. The descent order is as follows: 2 upper step support (10.5 m) > 4 lower step support (4.02 m) > 1 upper step excavation (3.52 m) > 3 lower step excavation (2.64 m) > 5 inverted arch excavation (1.94 m). The daily average descent frequency is from large to small: 1 upper step excavation (3.52 m/d) > 3 lower step excavation (2.64 m/d) > 2 upper step support (2.1 m/d) > 5 inverted arch excavation (1.94 m/d) > 4 lower step support (0.8 m/d).

Through the above analysis, it can be concluded that the excavation and support of the upper steps have the highest impact on the groundwater level. With the total maximum water level drawdown of 14.02 m, the daily average rate of water level decline is also large. The lowest groundwater level decreases by 6.66 m in these two stages, and the daily average decline rate of water level is lower than that of the corresponding stage of the upper step. For the (1) - (4)





Figure 7. Groundwater level versus time during construction.

20

30

40

Time/d

50

10

-25 L 0

60

70

construction stage, the daily average water-level decline rate of each excavation stage is greater than that of the corresponding support stage, while due to the relationship between the process length, the water level decline of each support stage is greater than that of the corresponding excavation stage.

For (6) - (8) construction stage, that is, after the inverted arch support is completed, the groundwater level begins to increase gradually. When the inverted arch support is completed, the lowest groundwater level is 18.6 m, which is 4.02 m higher than that of the previous stage. When the inverted arch lining is completed, the lowest groundwater level is 9.26 m, which is 9.34 m higher than that of the previous stage. After the completion of the arch wall lining, the secondary lining is closed into a circle. Due to the water separation effect of the water reproof board, the groundwater cannot penetrate into the tunnel, and the water level gradually returns to the initial state. In the process of groundwater level recovery, the rate of water level rise decreases with time.

3.1.3. Variation of Pore Water Pressure

Figure 8 depicts the pore water pressure distribution of mining method tunnel construction in weathered granite in different stages. Before the tunnel is excavated, the pore water pressure increases linearly from top to bottom along with the vertical direction. The pore water pressure of the initial surface water level is 0 MPa, and the bottom of the model is 2 MPa.

From **Figure 8(a)**, when the upper step is excavated (t = 1 d), the excavation surface is a free drainage interface, the pore water pressure is 0 MPa, the groundwater level begins to decline, and the pore water pressure above the water level is negative.

From Figure 8(b) when the upper step support is completed (t = 6 d), the inner circle of the initial support and the excavation bottom face are free drainage interface and the pore water pressure is 0 MPa. At this time, the maximum pore water pressure around the tunnel is located at the external vault of the initial support, $P_{max} = 0.13$ MPa.

From Figure 8(c), when the next step is excavated (t = 7 d), the free drainage interface is the initial support inner circle of the upper step and the excavation surface of the lower step. The pore water pressure on the interface is 0 MPa, and the maximum pore water pressure around the tunnel is located at the archtop external side of the initial support, $P_{max} = 0.06$ MPa.

From **Figure 8(d)**, when the current step support is completed (t = 12 d), the free drainage interface is the inner circle of the initial support of the upper and lower steps and the bottom of the excavation of the lower steps. The pore water pressure on the interface is 0 MPa, and the maximum pore water pressure around the tunnel is located at the archtop of the external side of the initial support, $P_{max} = 0.10$ MPa.

From **Figure 8(e)**, when the inverted arch is excavated (t = 13 d), the inner circle of the initial support of upper and lower steps and the excavation face of the inverted arch is free drainage interfaces, and the pore water pressure is 0 MPa.







The maximum pore water pressure around the tunnel is still located at the external vault of the initial support, $P_{max} = 0.05$ MPa.

From **Figure 8(f)**, when the inverted arch support is completed (t = 15 d), the initial support is sealed into a circle, the inner circle of the support is a free drainage interface, the pore water pressure is 0 MPa, and the maximum pore water pressure around the tunnel transfers to the external arch bottom of the initial support, $P_{max} = 0.28$ MPa. The pore water pressure around the tunnel appears more than in the previous stage, there is a significant increase.

From Figure 8(g) and Figure 8(h), with the construction of the inverted arch and arch wall lining, the distribution of pore water pressure gradually restores to its initial state. When the inverted arch lining is completed (t = 35 d), the maximum pore water pressure around the tunnel is located at the external arch bottom of the tunnel, $P_{max} = 0.37$ MPa. After the arch wall lining is completed, the secondary lining is sealed into a circle, and the tunnel waterproof structure completely isolates the tunnel inner from groundwater. As time goes on, the groundwater level basically restores to the initial state (t = 3 a). Finally, the secondary lining needs to bear a large pore water pressure. The pore water pressure value of the external arch bottom of the tunnel is the largest, $P_{max} = 0.46$ MPa.

3.1.4. Variation of Groundwater Flow Velocity

The variation of the groundwater seepage velocity can better reflect the law of groundwater flow in different stages of tunnel construction by the mining method. **Figure 9** depicts the vector diagram of groundwater flow velocity in different stages of mining method tunnel construction in weathered granite.

According to **Figure 9(a)**, when the excavation of the upper step of the tunnel is completed (t = 1 d), groundwater flows into the tunnel from all directions through the excavation face of the upper step. At this time, the groundwater flow velocity at the arch foot of the excavation face is the highest, $v_{max} = 1.254e^{-4}$ m/s.

According to **Figure 9(b)**, when the mitial support of the upper step is completed (t = 6 d), it is difficult for groundwater to flow directly into the tunnel from the initial support because of the feeble permeability of the shotcrete. It flows mainly through the bottom of the upper step excavation, especially at the junction of the initial support and the excavation bottom, $v_{max} = 3.057e^{-4}$ m/s.

According to Figure 9(c), when the excavation of the lower step of the tunnel is completed (t = 7 d), the groundwater velocity increases gradually from the top of the tunnel to both sides of the excavation face of the lower step. The overall direction of the velocity vector shows that groundwater flows into the tunnel mainly through both sides of the lower step excavation face and the arch foot of the bottom. The initial support of the upper step intersects with the excavation face of the lower step. The groundwater velocity at the boundary is the highest, $v_{max} = 1.697e^{-4}$ m/s.

According to **Figure 9(d)**, when the initial support of the lower step is completed (t = 12 d), groundwater will converge along with the initial support to the bottom of the lower step excavation and flow into the tunnel at the junction of the initial support, while groundwater under the excavation bottom flows upward. The maximum groundwater velocity appears at the junction of the bottom of the lower step excavation and the initial support, $v_{max} = 6.562e^{-4}$ m/s.

According to **Figure 9(e)**, when the tunnel invert excavation is completed (t = 13d), groundwater flows into the tunnel from the tunnel vault along with the upper and lower steps of the initial support to the bottom of the arch. At this time, the groundwater flow velocity at the junction of the initial support and the invert excavation surface is the highest, $v_{max} = 1.991e^{-4}$ m/s.





Figure 9. Vector map of groundwater flow velocity (m/s) for each construction stage. (a)Upper step excavation (t = 1 d); (b) upper stage support (t = 6 d); (c) Excavation of lower steps (t = 7 d); (d) Lower step support (t = 12 d); (e) Invertedarch excavation (t = 13 d); (f) Inverted arch support (t = 15 d); (g) Invertedarch lining (t = 35 d); (h) Arch wall lining (t = 3 a).

According to **Figure 9(f)**, when the inverted arch support is completed (t = 15 d), the initial support is sealed, and part of groundwater begins to flow upward

along both sides of the arch wall, which indicates that the groundwater level begins to rise gradually, but the flow velocity in this stage is significantly lower than that in the previous stage. The maximum groundwater flow velocity appears on both sides of the initial support of the upper step, $v_{max} = 3.332e^{-7}$ m/s. In addition, another part of groundwater seeps into the tunnel through the initial support, but the seepage velocity is very small.

According to **Figure 9(g)**, after the inverted arch lining is applied (t = 35 d), groundwater flows from bottom to top along with the initial support due to the water-resistant effect of the bottom waterproof board. Some of the groundwater seeps into the tunnel through the initial support of the upper and lower steps, while the other part continues to flow upwards. In this stage, the groundwater flows velocity further decreases, and the maximum flow velocity is located at the junction of the initial support of the upper and lower steps, $v_{max} = 8.519e^{-7}$ m/s.

According to **Figure 9(h)**, when the arch wall liming is applied, the second lining is sealed into a circle, and the groundwater is completely isolated by the fully sealed waterproof structure. As time goes on, the groundwater level restores to its initial state (t = 3 a), and the flow velocity is approximately 0 m/s.

3.2. Sensitivity Analysis of Seepage Field to Various Influencing Factors during Construction

(Note: from this section to the end of our work, all related figures (10 - 29) can be found in the appendices)

The sensitivity of the seepage field to various influencing factors during tunnel construction is the basis of evaluating the negative effect of tunnel construction on the groundwater environment. There are many influencing factors in the seepage field, so it is necessary to classify the influencing factors first, and then select representative and practical influencing factors from various factors to carry out the corresponding sensitivity analysis. Based on the geological condiions and engineering characteristics of the study area, combined with relevant research results ([9] [10] [11]), the influencing factors of the seepage field are divided into four categories: natural environment factors, engineering geology and hydrogeology factors, tunnel excavation factors and tunnel waterproof and drainage factors. Natural environment factors include rainfall, surface water system and other influencing factors. Engineering geology and hydrogeology include surrounding rock permeability, buried depth below water level and groundwater type. Tunnel excavation factors include parameters of the EDZ and excavation area. Tunnel waterproof and drainage factors include grouting circle parameters, shotcrete parameters and waterproof and drainage measures. Several representatives and practical influencing factors are selected from the above four types of influencing factors affecting the seepage field, and the sensitivity of seepage field to various influencing factors in the process of tunnel construction is analyzed to provide the basis for the evaluation of the influence of weathered granite tunnel construction on groundwater environment.



3.2.1. Sensitivity Analysis of Seepage Field to Natural Environmental Factors

Rainfall infiltration is one of the most important sources of groundwater supply. After the loss of surface evaporation and plant interception, part of rainfall infiltration into the aquifer is transformed into groundwater. The rainfall factor is the most representative factor among many natural environmental factors affecting the seepage field. The two most important indicators to measure the influence of rainfall factors on the seepage field are rainfall and rainfall infiltration coefficient. The sensitivity of the seepage field to monthly average rainfall and rainfall infiltration coefficient is analyzed by numerical examples in this section.

1) Sensitivity analysis of seepage field to monthly average rainfall

Firstly, the sensitivity of the seepage field to monthly average rainfall is investigated. Based on the seepage numerical calculation model, the surface flow boundary conditions of the original computation model are modified by taking into account three cases of monthly average rainfall: 30 mm (dry season), 90 mm (normal season) and 150 mm (flood season), respectively. The modified fixed flow boundary conditions are $2e^{-4}$ m/d (dry season), $6e^{-4}$ m/d (level season) and $1e^{-3}$ m/d (flood season). Figure 10 depicts a comparison chart of tunnel seepage flow at different construction stages under different monthly average rainfall. Figure 11 depicts a comparison chart of the maximum water level drawdown in different construction stages under different monthly average rainfall.

From Figure 10 and Figure 11, it can be seen that the tunnel seepage flow increases with the increase of rainfall, and the maximum water level decreases with the increase of rainfall. When the rainfall increases from 30 mm to 150 mm, the seepage flow increases by 0.5% in stage (1) of construction, and then gradually increases to 10.8% in stage (5) of construction. The decreasing range of the maximum water level is also gradually increasing, which shows that with the construction, the influence of rainfall on the seepage field is gradually increasing. During the flood season, the seepage rate of the tunnel is greater than that of the







Figure 11. Comparison chart of maximum water level drawdown in each construction stage under different monthly average rainfall.

tunnel during the dry season. However, the maximum water level by mining method construction in flood season is less than that in the dry season. This result indicates that tunnel construction by mining method in the flood season will cause more serious loss of groundwater resources, and the decline of groundwater level caused by mining method construction in the dry season is more significant.

Based on the above analysis, it can be concluded that the seepage field is sensitive to the variation of rainfall. The amount of groundwater resource loss caused by the mining method increases with the increase of rainfall, while the maximum water level decreases with the increase of rainfall. From the point of view of protecting the groundwater environment, the completion of tunnel construction before entering the flood season can avoid the most serious loss of groundwater resources, and is conducive to the rapid recovery of groundwater level.

2) Sensitivity analysis of seepage field to rainfall infiltration coefficient

Then, the sensitivity of the seepage field to the rainfall infiltration coefficient is investigated. The rainfall infiltration coefficient is 0.1, 0.2 and 0.3 respectively. The monthly average rainfall is 90 mm. The surface flow boundary conditions of the original calculation model are modified. The modified fixed flow boundary conditions are $3e^{-4}$ m/d, $6e^{-4}$ m/d and $9e^{-4}$ m/d, respectively. Figure 12 depicts a comparison chart of tunnel seepage flow at different construction stages under different rainfall infiltration coefficient. Figure 13 depicts a comparison chart of the maximum water level drawdown in different construction stages under different rainfall coefficient.

According to Figure 12 and Figure 13, with the increase of rainfall infiltration coefficient, the seepage flow of tunnels in each construction stage increases, and the maximum water level decreases. When the rainfall infiltration coefficient increases from 0.1 to 0.3, the tunnel seepage flow increases by 0.3% in stage 1 of construction, and then gradually increases to 6.7% in stage 5 of construction. The decreasing range of maximum water level decreases gradually





Figure 12. Comparison chart of tunnel seepage flow in different construction stages under different rainfall infiltration coefficients.





with construction, which indicates that the sensitivity of the seepage field to rainfall infiltration coefficient increases with time.

Mining method construction in the stratum with a high rainfall infiltration coefficient will lead to more serious groundwater loss, while mining method construction in the stratum with a low rainfall infiltration coefficient will cause a more significant groundwater level decline. Generally speaking, the sensitivity of seepage field to rainfall infiltration coefficient is similar to that to rainfall, but considering that the variation of rainfall is much stronger than that of rainfall infiltration coefficient in practice, the rainfall should take precedence over rainfall infiltration coefficient in evaluating the influence of rainfall factors on seepage field during tunnel construction.

3.2.2. Sensitivity Analysis of Seepage Field to Engineering Geology and Hydrogeological Factors

Engineering geology and hydrogeology are important factors affecting the variation of the seepage field. Among them, the permeability coefficient of surround-



ing rock and the depth below the water level of the tunnel are closely related to the design and construction of the tunnel. The sensitivity of the seepage field to the permeability coefficient of surrounding rock and the depth below the water level is analyzed by numerical examples in this section.

1) Sensitivity analysis of seepage field to permeability coefficient of the surrounding rock

In order to clarify the sensitivity of seepage field to the permeability coefficient of the surrounding rock, based on the numerical computation model, the permeability coefficient k_s of the stratum in which the tunnel is located is calculated with 0.1 m/d, 0.5 m/d, and 1 m/d, respectively. Figure 14 depicts a comparison chart of tunnel seepage at different construction stages under different permeability coefficients of surrounding rocks. Figure 15 depicts a comparison chart of maximum water level drawdown at different construction stages under different different permeability coefficients of surrounding rocks.



Figure 14. Comparison diagram of tunnel seepage flow in different construction stages under different permeability coefficient of the surrounding rock.



Figure 15. Comparison diagram of maximum drawdown in each construction stage under different permeability coefficient of the surrounding rock.

From Figure 14 and Figure 15, it can be seen that the seepage flow and the maximum water level drawdown increase with the increase of the permeability coefficient of surrounding rock in each construction stage. When the permeability coefficient of surrounding rock increases from 0.1 m/d to 1 m/d, the increase of tunnel seepage in the first five construction stages is 504.6%, 658.8%, 597.7%, 412.0%, 345.9%, respectively. The increase of maximum water level drawdown in the first seven construction stages is 767.9%, 714.6%, 713.3%, 542.4%, 595.5%, 371.5% and 286.3%, respectively. The variation of the permeability coefficient of surrounding rock is very sensitive. When the permeability coefficient of surrounding rock is large, the variation of tunnel seepage flow and maximum water level drawdown between different construction stages is much larger than that when the permeability coefficient of surrounding rock is small. Taking the maximum water level drawdown as an example, when the permeability coefficient of surrounding rock is 1 m/d, the maximum water level drawdown in stage (1) is 4.6 m, the maximum water level drawdown in stage (2) is 27.54 m, which increases by 22.94 m. And when the permeability coefficient of surrounding rock is 0.1 m/d, the maximum water level drawdown in stage ① is 0.53 m, and the maximum water level drawdown in stage (5) is 3,96 m, which increases of 3.43 m.

To sum up, the influence of the surrounding rock permeability coefficient on the seepage field is very significant. In the stratum with a large permeability coefficient, such as strongly weathered and moderately weathered granite stratum, mining method construction will cause serious loss of groundwater resources, significantly reduce groundwater level, and produce a strong negative effect on groundwater environment.

2) Sensitivity analysis of seepage field to a depth below water level

In order to obtain the sensitivity of the seepage field to the depth of tunnel underwater level, based on the numerical calculation model in this paper, the depth of tunnel roof underwater level is 10 m, 40 m, and 70 m, respectively. In order to eliminate the extra influence caused by the variation of stratum thickness, the three strata in the original model are merged into one stratum, and the physical and mechanical parameters are unified to take the parameters of moderately weathered granite. **Figure 16** depicts a comparison chart of tunnel seepage at different construction stages under different water levels. **Figure 17** depicts a comparison chart of the maximum water level drawdown in different construction stages with different depth below water level.

According to the above analysis, the seepage field has a very strong sensitivity to the depth below the water level of the tunnel. Mining method construction is carried out at the position below the water level where the depth is smaller. At the beginning of construction, the groundwater level decreases significantly, and then fluctuations occur. The loss of groundwater resources in each stage is smaller, while the depth below the water level is larger. Large-scale mining method construction will result in a larger loss of groundwater resources and a more significant drawdown in groundwater level.





Figure 16. Comparison of tunnel seepage flow at different stages of construction under different water levels.





8. Sensitivity Analysis of Seepage Field to Tunnel Excavation Factors

Through previous analysis in this paper, it can be seen that the construction by mining method will disturb the surrounding rock of weathered granite in a certain range and forms an EDZ. The permeability of surrounding rock in this area is enhanced, which promotes groundwater influx into the tunnel to a certain extent and aggravates the impact of tunnel construction on the groundwater environment. The permeability and thickness of EDZ are the key parameters affecting the seepage field. In order to clarify the sensitivity of the seepage field to the parameters of the EDZ, the seepage calculation of the permeability and thickness of different EDZ is carried out respectively in this section.

1) Sensitivity analysis of seepage field to the permeability of EDZ

Firstly, the sensitivity of the seepage field to the permeability of the EDZ is investigated. The ratio of the permeability coefficient k_E to permeability coefficient k_S of surrounding rock in the EDZ is defined as n_E . Based on the numerical



calculation model, n_E is taken as 1, 4, 7 and 10 for computation. Figure 18 depicts a comparison chart of tunnel seepage flow at different construction stages under different EDZ permeability. Figure 19 depicts a comparison chart of the maximum water level drawdown in different construction stages under the permeability of different EDZ.

According to **Figure 18** and **Figure 19**, it can be seen that with the increase of permeability of EDZ, the seepage flow and the maximum water level drawdown gradually increase in each construction stage. When n_E increases from 1 to 10, the seepage increase of the first five construction stages are 11.8%, 26.2%, 23.3%, 30.9% and 37.8%, respectively. The maximum water level drawdown increases of the first seven construction stages are 20.3%, 33.7%, 38.1%, 38.4%, 45.9%, 31.2% and 28.4%, respectively. With the increase of the excavation area, the sensitivity of the seepage field to the permeability of EDZ increases gradually and then decreases after initial support closure.







Figure 19. Comparison of the maximum water level drawdown in each construction stage under the permeability of different EDZ.

When $n_E = 1$, that is, without considering the influence of EDZ, the seepage flow of tunnel in stage (5) is 30.43 m³/d and the maximum water level drawdown is 16.98 m; when $n_E = 10$, the seepage flow of tunnel in stage (5) is 41.94 m³/d and the maximum water level drawdown is 24.77 m, increasing by 11.51 m³/d and 7.79 m, respectively. This shows that the seepage field is highly sensitive to the permeability of EDZ during tunnel construction. The greater the disturbance of mining method construction on the surrounding rock of weathered granite and the stronger the permeability of EDZ, the stronger the negative effect on the groundwater environment is, which will cause more serious groundwater resource loss and groundwater level decline.

2) Sensitivity analysis of seepage field to the thickness of EDZ

Then, the sensitivity of the seepage field to the thickness of EDZ (d_e) is investigated. d_E is taken as 0 m, 1 m, 1.5 m, and 2 m respectively. Figure 20 depicts a comparison chart of tunnel seepage at different construction stages under the different thicknesses of EDZ. Figure 21 depicts a comparison of maximum water level drawdown in different construction stages under the different thicknesses of EDZ.



Figure 20. Comparison of tunnel seepage flow at different construction stages under the different thickness of EDZ.



Figure 21. Comparison of the maximum water level drawdown in each construction stage under the thickness of different EDZ.

From Figure 20 and Figure 21, it can be seen that the seepage flow and the maximum water level drawdown increase with the increase of the thickness of EDZ. When d_E increases from 0 m to 2 m, the increase of seepage flow in the first five construction stages is 12.2%, 19.0%, 23.3%, 25.2% and 39.5%, respectively. The increase of maximum water level drawdown in the first seven construction stages is 24.4%, 25.1%, 30.5%, 28.3%, 36.2%, 25.7% and 25.5%, respectively. Before the initial support closing, with the tunnel excavation proceeding, the damaged area is gradually enlarged, and the influence of the thickness of the damaged area on the seepage field is gradually increased, while the effect of the initial support closure is gradually reduced.

When $d_E = 0$ m, that is, without considering the influence of EDZ, the seepage flow of tunnel in stage (5) is 30.43 m³/d and the maximum water level drawdown is 16.98 m. When $d_E = 2$ m, the seepage flow of tunnel in stage (5) is 42.44 m³/d and the maximum water level drawdown is 23.12 m, increasing by 12.01 m³/d and 6.14 m, respectively. Compared with the construction in **Figure 19** and **Figure 21**, the increment of maximum water level drawdown can be obtained, and the sensitivity of the seepage field to the thickness of EDZ is slightly weaker than to the permeability of EDZ.

If the thickness of EDZ formed by the miming method is bigger, the loss of groundwater resources and water level drawdown will be bigger, and the impact on the groundwater environment will be more serious. In conclusion, it can be seen from the analysis that the EDZ formed by mining method tunnel construction in weathered granite will increase the tunnel seepage flow and the maximum water level drawdown to a certain extent, and the seepage field has a strong sensitivity to the variation of EDZ parameters, so the parameters of EDZ need to be considered in the evaluation of the negative effect of groundwater environment.



3.4. Sensitivity Analysis of Seepage Field to Tunnel Waterproof and Drainage Factors

A waterproof system usually consists of grouting circle, initial support shotcrete, waterproof layer, and secondary lining waterproof concrete. According to whether the drainage blind pipe is installed, it can be divided into two categories: drainage type and fully sealed type. Grouting circle and shotcrete play an important role in water-resistance during tunnel excavation and support and have great significance in improving the seepage field. The following numerical examples are used to study the sensitivity of the seepage field to grouting circle and shotcrete parameters in this section.

1) Sensitivity analysis of seepage field to grouting circle parameters

Forming a grouting circle around the tunnel by means of advanced grouting can effectively reduce the adverse impact of EDZ on the seepage field, reduce the seepage flow of the tunnel, and reduce the impact of tunnel construction on the groundwater environment. The grouting effect depends on the impermeability and thickness of the grouting circle. In order to obtain the sensitivity of the seepage field to grouting circle parameters, different grouting circle impermeability and thickness are selected for calculation and analysis.

Firstly, the sensitivity of the seepage field to the impermeability of the grouting circle is investigated. The ratio of permeability coefficient k_S of surrounding rock and permeability coefficient k_G of grouting circle is defined as n_G and n_G is taken as 1, 10, 50, and 100, respectively, and the thickness of grouting circle $d_G =$ 2 m for computation. Figure 22 depicts the comparison chart of tunnel seepage flow in each construction stage under different grouting circle impermeability. Figure 23 depicts the comparison chart of the maximum water level drawdown in each construction stage under the impermeability of different grouting circles.

From Figure 22 and Figure 23, it can be seen that the seepage flow and the maximum water level drawdown of the tunnel in each construction stage decrease with the increase of the impermeability of the grouting circle. When n_G increases from 1 to 100, the seepage flow decrease in the first five construction stages are 53.5%, 27.8%, 79.1%, 71.0% and 96.4%, respectively. The maximum water level decrease in the first seven construction stages are 77.6%, 41.9%,







Figure 23. Comparison chart of maximum water level drawdown in each construction stage under different grouting circle impermeability.

49.1%, 57.6%, 60.5%, 61.5%, and 59.1%, respectively. This indicates that the seepage field is sensitive to the impermeability of the grouting circle, but this sensitivity gradually decreases with the increase of n_{G} .

When $n_G = 1$, the maximum water level drawdown from stage (2) to stage (5) is 14.02 m, 16.66 m, 20.68 m, and 22.62 m, respectively. When $n_G = 100$, the maximum water level drawdown from stage (2) to stage (5) is 8.14 m, 8.48 m, 8.76 m, and 8.93 m, respectively. It can be seen that with the increase of impermeability of grouting circle, the variation range of the maximum water level drawdown in different construction stages gradually becomes gentle. When n_G increases from 1 to 100, the seepage flow of the tunnel in stage (5) decreases from 40.72 m³/d to 1.45 m³/d, decreasing by 39.27 m³/d. And the maximum water level drawdown decreases from 22.62 m to 8.93 m, decreasing by 13.69 m. According to the above analysis, prior to the tunnel excavation, advanced grouting circle should be improved to a certain extent. This can effectively alleviate the phenomenon of groundwater resource loss and groundwater level decline caused by mining method construction.

Then, the sensitivity of the seepage field to grouting circle thickness is investigated, and d_G is taken as 0 m, 2 m, 4 m, 6 m, and $n_G = 10$. Figure 24 depicts a comparison chart of tunnel seepage in different construction stages under different grouting eircle thickness. Figure 25 depicts a comparison chart of maximum water level drawdown in different construction stages under different grouting circle thickness.

From Figure 24 and Figure 25, with the increase of grouting circle thickness, tunnel seepage, and maximum water level drawdown gradually decrease in each construction stage When d_G increases from 0m to 6m, the seepage decrease in the first five construction stages is 53.5%, 34.1%, 55.8%, 45.9% and 84.1%, respectively. The maximum water level decrease in the first seven construction







Figure 25. Comparison chart of the maximum water level drawdown in each construction stage under different grouting circle thickness

stages is 75.6%, 49.1%, 52.4%, 51.0%, 54.2%, 49.7%, and 48.4%, respectively. The seepage field has a strong sensitivity to grouting circle thickness, especially when d_G increases from 0 m to 2 m, tunnel seepage flow, and maximum water level drawdown are significantly reduced, but with the further increase of d_G the sensitivity gradually declines.

When d_G increases from 0m to 6m, the seepage of the tunnel in stage (5) decreases from 40.72 m³/d to 6.47 m³/d, it decreased by 34.25 m³/d. And the maximum water level decreases from 22.62 m to 10.36 m, it decreased by 12.26m. Comparing the variation range of the seepage flow and the maximum water level drawdown in each construction stage under different grouting circle impermeability and thickness, it can be concluded that the sensitivity of the seepage field to the thickness of grouting circle is weaker than that to the impermeability of grouting circle. According to the above analysis, the seepage field has a strong sensitivity to the parameters of the grouting circle. The grouting circle with certain impermeability and thickness can effectively alleviate the adverse impact of the mining method construction on the groundwater environment, reduce the seepage flow and water level drawdown of the tunnel.

2) Sensitivity analysis of seepage field to shotcrete parameters

Through analysis in this paper, it can be seen that after the initial support closure, the seepage of tunnel decreases rapidly, the groundwater level gradually increases, and the performance of shotcrete plays a key role in this process. The impermeability and thickness of shotcrete are important parameters affecting the seepage field. In order to obtain the sensitivity of the seepage field to the parameters of shotcrete, different impermeability and thickness of shotcrete are selected for calculation and analysis in this section.

Firstly, the sensitivity of the seepage field to the impermeability of shotcrete is investigated. The ratio of permeability coefficient k_s of surrounding rock to permeability coefficient k_c of shotcrete is defined as n_c which is taken as 100,



1000, and 10,000, respectively. And the thickness of shotcrete $d_G = 15$ cm for calculation. Figure 26 depicts the comparison chart of tunnel seepage flow in each construction stage under different impermeability of shotcrete. Figure 27 depicts a comparison chart of the maximum water level drawdown in each construction stage under different impermeability of shotcrete.

From Figure 26, when n_c increases from 100 to 1000, the variation ranges of tunnel seepage flow in support stage 2 and 4 are -5.2% and -4.8%, respectively. While in excavation stage 1, 3, and 5, the variation ranges of tunnel seepage flow are 0%, 0.1%, and +0.7%, respectively. The permeability coefficient of shotcrete has a slight influence on the seepage flow of the tunnel in the support stage but has little influence on the seepage flow in the excavation stage.

From Figure 27, it can be seen that the impermeability of shotcrete has little influence on the maximum water level drawdown before the initial support







Figure 27. Comparison chart of maximum water level drawdown in each construction stage under different impermeability of shotcrete.

closure. When n_C increases from 100 to 1000, the maximum water level drawdown range of the first five construction stages is 0%, 3.3%, 2.6%, 4.5%, and -3.8%, respectively. After the initial support is sealed, the influence of the impermeability of shotcrete on the maximum water level drawdown is gradually obvious. The variation ranges of the maximum water level drawdown in stage (6) and (7) are - 12.1% and - 50.6%, respectively. The effect of shotcrete impermeability on the groundwater environment is mainly embodied in the later stage of tunnel construction. Taking the maximum water level drawdown of stage (7) as an example, when shotcrete impermeability is strong ($n_C = 10,000$), the maximum water level in this stage falls to 9.14 m, and the recovery degree of groundwater is much greater than that of shotcrete when its impermeability is weak($n_C = 100$).

From Figure 28 and Figure 29, the sensitivity of the seepage field to shotcrete thickness is very weak in each construction stage. When d_c increases from 10 cm







Figure 29. Comparison chart of maximum water level drawdown in each construction stage under different shotcrete thickness.

to 30 cm, the variation ranges of tunnel seepage flow in the first five construction stages are 0%, 0.4%, 0.3%, 0.5%, and -0.4%, respectively. In the first seven construction stages, the maximum water level drawdown increases by 0%, -2.3%, -2.0%, -1.3%, -1.5%, -1.7%, -3.1% respectively. To sum up, the influence of shotcrete parameters on the seepage field is mainly determined by its impermeability, and the influence of thickness is very limited.

4. Conclusions

In this paper, based on the engineering background of weathered granite tunnel, according to the construction characteristics of mining method, the seepage model of equivalent continuous medium tunnel is established by using the finite element software ABAQUS, and the variation law of seepage field in the process of mining method construction of weathered granite tunnel is simulated, and the sensitivity of seepage field to various influencing factors in the process of construction is analyzed, and the following conclusions are obtained.

During the construction of the weathered granite tunnel by mining method, the loss of groundwater resources and the decline of groundwater level mainly occurred in the construction stage before the initial support closure. During this period, the daily average seepage flow and the groundwater level decline showed a trend of fluctuation and decrease. When the initial support is sealed and formed into a circle, the seepage flow of the tunnel decreases sharply. After that, the influence of the tunnel construction on the groundwater environment is very small, and the groundwater level increases gradually.

From the completion of the initial support of the upper steps to the closure of the initial support, the maximum value of pore water pressure around the tunnel is always located at the external vault of the initial support of the upper steps, and the maximum value of groundwater velocity is located at the junction of the initial support and excavation surface, both of which present a fluctuating trend. When the initial support is closed, the maximum pore water pressure around the tunnel increases sharply and transfers to the outside arch bottom of the initial support. With the rise of the groundwater level, the groundwater flow rate decreases sharply. With the gradual recovery of the groundwater level, the groundwater flow rate approaches 0.

In the process of mining method construction, the seepage field has a certain sensitivity to the rainfall factors. The tunnel seepage flow increases with the increase of rainfall and rainfall infiltration coefficient, and the maximum water level drawdown decreases with the increase of rainfall and rainfall infiltration coefficient. The sensitivity increases with the increase of time. Mining method construction in the rainy season will cause more serious loss of groundwater resources, however, the phenomenon of groundwater level decline caused by mining method construction in the dry season is more significant. The completion of tunnel construction before entering the flood season can avoid the most serious loss of groundwater resources, and is conducive to the rapid recovery of



groundwater level.

The seepage field is very sensitive to the permeability coefficient of surrounding rock and the buried depth below the water level in the process of mining method construction. The seepage flow and the maximum water level drawdown increase with the permeability coefficient of surrounding rock and the buried depth below the water level. The larger the permeability coefficient of surrounding rock is, the more obvious the change of tunnel seepage flow and maximum drawdown between different construction stages is. For the tunnel with small buried depth below the water level, the groundwater level draws down significantly at the initial stage of construction, and the amount of groundwater resource loss in each stage is small, while the mining method construction at the location with large buried depth below the water level will produce a large amount of groundwater resource loss, and the groundwater level drawdown is more significant.

The seepage field has a strong sensitivity to the parameters of EDZ formed in the process of mining construction. The seepage flow and the maximum water level drawdown of the tunnel increase with the increase of the permeability and thickness of the EDZ. The sensitivity increases with the expansion of the excavation area and gradually weakens after the initial support closure. The seepage field has a strong sensitivity to the parameters of the grouting circle. The seepage flow and the maximum water level drawdown of the tunnel decrease with the increase of the impermeability and thickness of the grouting circle. The construction of a certain impermeability and thickness of the grouting circle can effectively alleviate the adverse impact of EDZ on the groundwater environment, and significantly reduce the seepage flow and groundwater level drawdown of the tunnel.

Before the initial support is closed, the sensitivity of the seepage field to the parameters of shotcrete is very weak. When the initial support is closed, the sensitivity of the seepage field to the impermeability of shotcrete is gradually increased. With the increase of the impermeability of shotcrete, the recovery speed of the groundwater level is significantly accelerated, and the influence of shotcrete thickness on the seepage field is very limited.

Acknowledgements

Sino-Cameroon Cooperation through the Chinese Scholarship Council Program and 108 Research Group (Hohai University) supported much of the work presented in this paper. The authors would like to express appreciation to the reviewers for their valuable comments and suggestions that helped to improve the quality of the paper.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.



References

- Ii, H. and Kagami, H. (1997) Groundwater Level and Chemistry Changes Resulting from Tunnel Construction near Matsumoto City. *Environmental Geology*, 31, 76-84. <u>https://doi.org/10.1007/s002540050166</u>
- [2] Lipponen, A.M. (2001) Application of Rock Fracturing Data from the Päijänne Tunnel Construction: Environmental Analysis. Pascal and Francis Bibliographic Databases, 687-691.
- [3] Chae, G.T., *et al.* (2008) Hydrochemistry of Urban Groundwater Seoul, Korea: The Impact of Subway Tunnels on Groundwater Quality. *Journal of Contaminant Hydrology*, **101**, 42-52. <u>https://doi.org/10.1016/j.jconhyd.2008.07.008</u>
- [4] Vincenzi, V., et al. (2009) Using Tracer Tests and Hydrological Observations to Evaluate Effects of Tunnel Drainage on Groundwater and Surface Waters in the Northern Apennines. Hydrogeology Journal, 17, 135-150. https://doi.org/10.1007/s10040-008-0371-5
- [5] Raposa, J.R., *et al.* (2010) Quantitative Evaluation of Hydrogeological Impact Produced by Tunnel Construction Using Water Balance Models. *Engineering Geology*, 116, 323-332. <u>https://doi.org/10.1016/j.enggeo.2010.02.014</u>
- [6] Wang, W.Z. (2013) Study on the Interaction between Tunnel Construction and Groundwater Environment. Thesis-Chinese, Shijiazhuang Railway University, Shijiazhuang.
- [7] Yuan, Y.X. (2003) Environmental Problems and Countermeasures during the Construction of Wuqiaoling Tunnel. Thesis-Chinese, Southwest Jiaotong University, Chengdu.
- [8] Wang, C.X., et al. (2008) Prediction of Water Gushing in Long Tunnel under Complex Conditions and Its Environmental Impact Assessment (Chinese). Journal of Rock Mechanics and Engineering, 27, 2411-2417.
- [9] Liu, Z.C. (2015) Study on the Interaction Mechanism and Control Technology between Fractured Rock Mass Tunnel and Groundwater Environment. Beijing Jiaotong University, Beijing.
- [10] Liu, J. and Liu, D. (2012) Evaluation of Negative Environmental Effects of Groundwater Drainage in Gele Mountain Tunnel of Yuhuai Railway. *Modern Tunneling Technology*, **49**, 178-183.
- [11] Jiang, Z.X. (2005) The Interaction between Tunnel Engineering and Water Environment (Chinese). *Journal of Rock Mechanics and Engineering*, **24**, 121-127.