International Journal of Transportation Engineering and Technology
2018; 4(4): 75-82
http://www.sciencepublishinggroup.com/j/ijtet
doi: 10.11648/j.ijtet.20180404.12
ISSN: 2575-1743 (Print); ISSN: 2575-1751 (Online)

The Effect of Groundwater Seepage on Stability of Tunnel by Using Strength Reduction Method Considering Fluid Solid Coupling

Zhaobing Zhang[1, 2, 3], Xiaoguang Jin[1, 2, 3, *], Yayong Li[4], Zhongya Zhang[1, 2, 3]

[1]School of Civil Engineering, Chongqing University, Chongqing, China
[2]Key Laboratory of New Technology for Construction of China in Mountainous Area, Chongqing University, Chongqing, China
[3]National Joint Engineering Research Center of Geohazards Prevention in the Reservoir Areas, Chongqing University, Chongqing, China
[4]China Construction Tunnel Corp., Ltd., Chongqing, China

Email address:
jinxiaoguang@cqu.edu.cn (Xiaoguang Jin)
[*]Corresponding author

To cite this article:
Zhaobing Zhang, Xiaoguang Jin, Yayong Li, Zhongya Zhang. The Effect of Groundwater Seepage on Stability of Tunnel by Using Strength Reduction Method Considering Fluid Solid Coupling. *International Journal of Transportation Engineering and Technology*. Vol. 4, No. 4, 2018, pp. 75-82. doi: 10.11648/j.ijtet.20180404.12

Received: December 2, 2018; **Accepted**: December 25, 2018; **Published**: January 22, 2019

Abstract: During the construction period of tunnels, groundwater seepage may lead to large deformation and even collapse of tunnel. To study the effect of groundwater seepage on stability of tunnel, the strength reduction method considering fluid solid coupling was employed to calculate safety factor of tunnel by using numerical simulation. Firstly, three working cases were established to investigate the effect of groundwater seepage and calculation mode on safety factor of tunnel. Then the fluid solid indirect coupling mode was adopted to investigate the relationship between safety factor and groundwater level. Numerical results show that safety factor considering groundwater seepage is about 20% less than that without considering groundwater seepage. Numerical results of two calculation modes are almost identical, but the computational time of fluid solid indirect coupling mode is far less compared with that of fluid solid coupling mode. Safety factor of tunnel linearly decreases with the increase of groundwater level, with the slope of 0.26. Moreover, tunnel crown settlement increases with the increase of groundwater level when the strength reduction factor is equal. Groundwater seepage is unfavorable to control tunnel deformation. In the watery zone, groundwater level should be lowered to improve stability of tunnel on condition that it does not seriously affect surrounding environment.

Keywords: Fluid Solid Coupling, Strength Reduction Method, Safety Factor, Groundwater Seepage

1. Introduction

The strength reduction method was first proposed by Zienkiewicz [1]. With the development of computer computing technology, finite element analysis has achieved rapid development. A group of scholars represented by Zheng et al. [2−5] have done a lot of research on the finite element strength reduction method. The results show that it is feasible to use the finite element strength reduction method to analyze the slope stability. For example, Zhao et al. [2] used the finite element method to obtain the slope safety factor by strength reduction. The calculation results are very close to the results of the traditional method. The strength reduction method is not only suitable for slope engineering, but also for tunnel engineering. Many scholars have done research in this area [6-8]. For example, Qiao et al. [6] applied the strength reduction method to the stability analysis of the shield tunnel excavation face, defined the concept of the stability safety factor of tunnel excavation face, and obtained the stability safety factor and potential sliding surface of the excavation face. Wu et al. [8] determined the stability coefficients of different excavation methods by strength reduction method, and compared the plastic zone area ratios of different parts after excavation and support, and determined the most suitable excavation method. The tunnel construction process is often accompanied by groundwater seepage (as shown in Figure 1). Large deformation and even instability of surrounding rock caused by groundwater seepage occur from time to time, which greatly aggravates the risk in tunnel construction. Previous studies [9-12] have shown that groundwater seepage caused by tunnel excavation and excavation will cause stress distribution of surrounding rock and have an important impact on the stability of tunnel surrounding rock. For example, Jin et al. [9] used numerical analysis method to study the water-force coupling effect of a cross-river tunnel excavation process. The results show that the groundwater seepage causes the displacement, stress and internal force of the surrounding rock of the tunnel to increase greatly. Liu et al. [12] studied the mechanical properties of tunnel structure when the stress field acted alone, the seepage field acted alone and the seepage field-stress field coupled together under the condition of group holes through numerical analysis. The results showed that the groundwater seepage had a great influence on the deformation and stress of surrounding rock. The existing research on the influence of groundwater seepage on tunnel stability mainly focuses on the study of displacement field, stress field and seepage field, while the research on the safety factor of unified index is relatively rare. In this paper, the strength reduction method considering fluid-solid coupling is applied to study the influence of groundwater seepage on tunnel stability. Analyze the influence of groundwater seepage and fluid-solid coupling calculation mode on tunnel safety factor, and reveal the inherent law of groundwater level and tunnel safety factor. The research results can provide theoretical basis and guidance for the design and construction of underwater tunnels.

Figure 1. *Photo of groundwater seepage in a tunnel.*

2. Strength Reduction Method Considering Fluid-Solid Coupling

2.1. Principle of Strength Reduction

In the calculation and analysis of the strength reduction method, the strength parameters of the rock and soil mass are reduced according to relationship shown as follow.

$$c' = \frac{c}{F} \tan\varphi' = \frac{\tan\varphi}{F} \tag{1}$$

Substituting the reduced parameters into the numerical model for trial calculation, and calculating the limit state of the near-destruction by gradually increasing the reduction coefficient, the corresponding reduction coefficient is the safety factor. At present, there are mainly three criteria for the safety factor of slope in the strength reduction method: 1) the displacement at the characteristic point is abrupt; 2) the generalized plastic strain or the equivalent plastic strain passes from the slope toe to the top of the slope. 3) numerical calculation does not converge [13]. Some studies have shown that the phenomenon of sliding through the plastic zone is only a necessary condition but not a sufficient condition for failure. However, the strain or displacement mutation on the sliding surface is often accompanied by non-convergence in numerical calculation, and the calculation results obtained from criterion 1 and criterion 3 are relatively consistent. In this paper, the sudden change of the characteristic point displacement of surrounding rock (vault settlement, horizontal displacement of the arch waist, etc.) is used as the instability criterion of the tunnel, and the reduction factor and critical slip surface of the tunnel are determined accordingly.

2.2. Implementation Process of Strength Reduction Method Considering Fluid-Solid Coupling

Most of the tunnel damage belongs to shear failure, and the reduction of tensile strength has little effect on the safety factor of the tunnel [14]. In this paper, only the shear strength parameters c and φ of the surrounding rock of the tunnel are reduced, and the calculated safety factor is Shear safety factor. The concrete realization process is as follows. Before the fluid-solid coupling analysis, the initial stress balance is calculated by using the reduced surrounding rock mechanical parameters, and the calculated node displacement, velocity and plastic zone are initialized. Then, the seepage mode is called, and the surrounding rock is set as an isotropic seepage model. The FISH language is used to program the assignment of the surrounding rock permeability coefficient, porosity, fluid modulus, fluid tensile strength, fluid density, and pore water pressure. The excavation of the tunnel is simulated by the passivation tunnel unit, and the pore water pressure at the circumferential boundary of the tunnel is set to zero. The seepage mode is then turned on for fluid-solid coupling calculations. The curve of the displacement of the characteristic point of the tunnel with the reduction factor is obtained by gradually increasing the reduction coefficient; the reduction coefficient corresponding to the position where the displacement-reduction coefficient curve is abrupt is the safety factor of the tunnel.

3. Influence of Groundwater Seepage on Tunnel Stability

3.1. Numerical Calculation Scheme

Using the international general geotechnical software FLAC3D for numerical calculation, FLAC3D as finite difference software can not only perform non-seepage mode calculation, but also provide fluid-solid indirect coupling (calculating the pore pressure field obtained by seepage first, then performing mechanical calculation) and direct fluid-solid coupling (the change of pore water pressure will cause mechanical deformation, and the volumetric strain will cause the pore water pressure to change) for fluid-solid coupling calculation. In order to study the influence of groundwater seepage and fluid-solid coupling calculation mode on tunnel safety factor, a circular tunnel is taken as an example to calculate the safety factor of the tunnel under three working cases (such as Table 1).

Table 1. *Working cases.*

Working case	Groundwater condition	Calculation mode
Working case 1	No groundwater	Not consider groundwater
Working case 2	Groundwater level is ±0.000 m (the upper surface of the model)	Fluid-solid indirect coupling
Working case 3		Direct fluid-solid coupling

3.2. Numerical Calculation Model

The characteristics of the tunnel surrounding rock in the longitudinal direction are basically same. To improve the calculation efficiency and accuracy, the solution of tunnel safety coefficient is treated as plane strain problem. The numerical calculation model is shown in Figure 2.

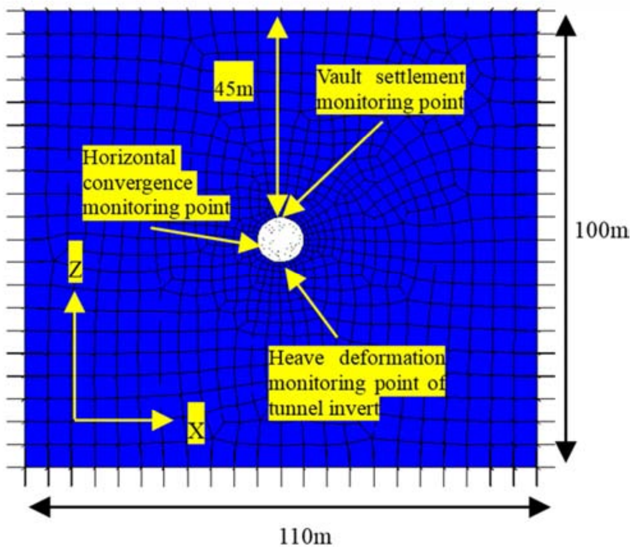

Figure 2. *The numerical model.*

The tunnel section is circular, with a radius of 5 m and a buried depth of 45 m. The model has 1,984 nodes and 950 units. In order to reduce the influence of boundary conditions on the calculation accuracy, the distance between the X-direction model boundary and the tunnel wall is 50 m (5 times hole diameter), and the distance between the upper boundary of the model and the lower boundary to the wall is 45 m (4.5 times hole diameter). According to the existing engineering experience and geological survey data, the physical and mechanical parameters of the surrounding rock used in the numerical simulation (as shown in Table 2). The model stress and seepage boundary conditions are as follows: the top of the model is free, the corresponding water level pore water pressure is fixed and the corresponding stress boundary conditions are applied; the X-direction horizontal displacement is fixed on both sides of the model, and the Z-direction displacement is restricted at the bottom of the model; both sides and bottom of the model are water-permeable boundaries. The pore water pressure of the surrounding rock before tunnel excavation is hydrostatic pressure. The initial vertical stress and lateral pressure of surrounding rock under saturated conditions can be obtained by equations (2) and (3).

$$\sigma_{zz} = \rho_{\mathrm{sat}} g z \tag{2}$$

$$\sigma_{xx} = \sigma_{yy} = k_0 \sigma'_{zz} = k_0(\rho_{sat} - \rho_w) g z \tag{3}$$

Where: σ_{zz} is the vertical ground stress of the rock mass; σ_{xx} and σ_{yy} are the horizontal ground stress; σ'_{zz} is the vertical effective ground stress; ρ_{sat} is the rock mass saturation density; ρ_w is the water density; g is the gravity acceleration; k_0 is lateral pressure coefficient (obtained by Poisson's ratio of rock mass); z is the buried depth at the calculated position.

Table 2. *Mechanical parameters of rock mass.*

Lithology	Elastic modulus /GPa	Poisson ratio	Cohesion /kPa	Friction angle /(°)	Permeability coefficient /$(m \cdot s^{-1})$
Sandy mudstone	6.0	0.3	1200	45	4.41×10-6

3.3. Numerical Model Validity Verification

The increment of the surrounding rock shear strain can be used not only to determine the safety factor of the tunnel, but also to determine the potential failure surface of the tunnel. Figure 3 and Figure 4 show the incremental shear strain cloud of the surrounding rock when the reduction factor is 1 and 6.55, respectively. It can be seen from the figure that when the strength reduction factor is 1, the tunnel shear strain increment is evenly distributed around the tunnel, and the shear strain increment is small, and the maximum value is only 2.26×10−4. When the strength reduction factor is 6.55, the shear strain increment is greatly increased, and the maximum value is located at the tunnel arch foot, the value is 0.1517; the tunnel surrounding rock will be lost along the critical state sliding surface shown in Figure 4. The incremental distribution of the tunnel shear strain and the shape of the critical failure surface in Figure 4 are basically consistent with those obtained by Zheng et al. [15] using geotechnical tests. This verifies the validity and correctness of using the strength reduction method considering fluid-solid coupling theory to solve the tunnel safety factor and critical failure surface.

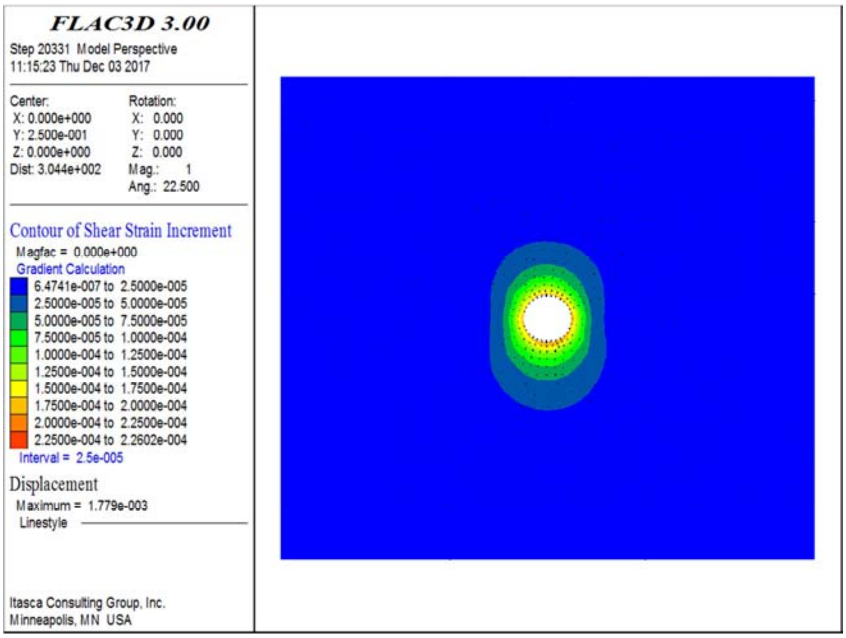

Figure 3. *Shear strain increment and displacement of surrounding rock when reduction factor is 1.*

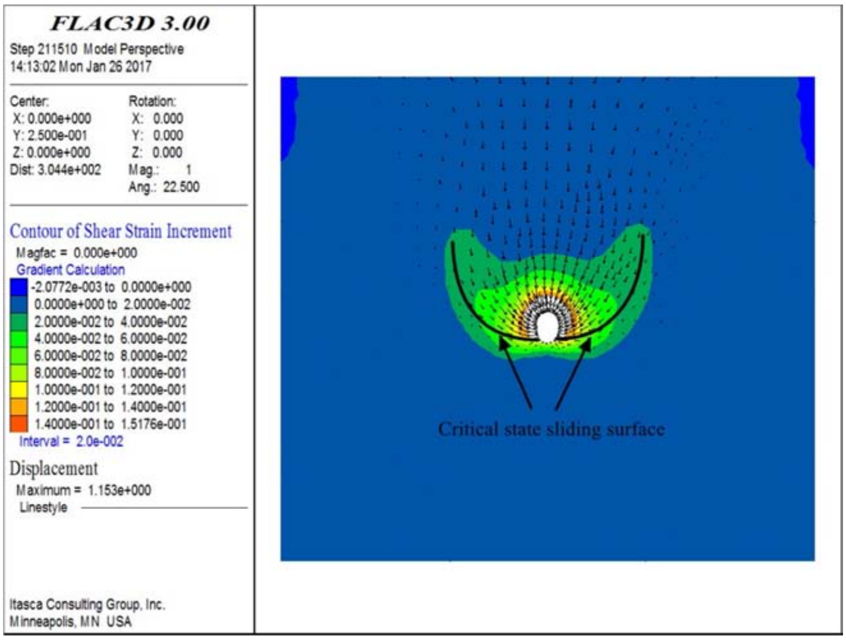

Figure 4. *Shear strain increment and displacement of surrounding rock when reduction factor is 6.55.*

4. Analysis of Calculation Results

The rock mass mechanical parameters are reduced by gradually increasing the reduction factor until the tunnel hole displacement is abrupt. In the numerical simulation, the displacements of the three monitoring points around the tunnel (as shown in Figure 2) are recorded. According to the calculation results, the curve of tunnel vault settlement, horizontal convergence and heave deformation of tunnel invert with the reduction factor is plotted. The corresponding reduction coefficient when the curve of the displacement - reduction coefficient changes suddenly is the safety coefficient of the tunnel.

4.1. Tunnel Safety Factor Under Working Case 1

Working case 1 is to calculate the initial geostress field using the dry density of the rock mass without considering the groundwater. Figure 5 shows the curve of the displacement of the three feature points around the tunnel with the reduction factor. It can be seen from Figure 5 that the deformation of the vault and the horizontal displacement of the arch waist are basically same. When the reduction factor is greater than 6.55, the deformation of the surrounding rock increases sharply. Therefore, the tunnel safety factor is 6.55 without considering groundwater conditions. It should be noted that when reduction factor is greater than 6.55, the tunnel arch bottom bulge does not increase significantly, because the tunnel will break along the critical slip surface shown in Figure 4 in the critical state. The monitoring point of the tunnel arch bottom is below the sliding surface, which is less affected by the instability of the tunnel, and the amount of uplift of the arch bottom is small.

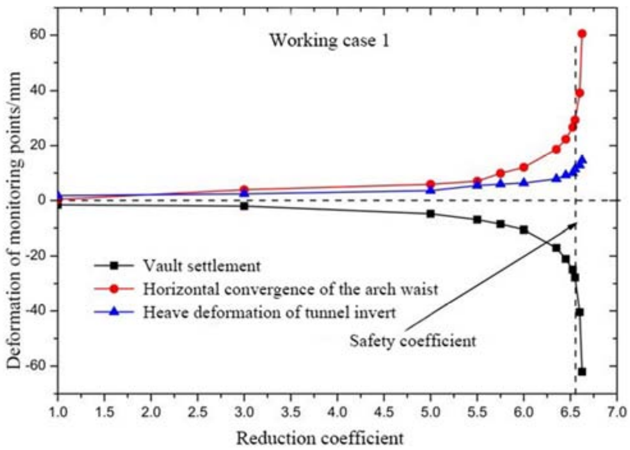

Figure 5. Curves of displacement with reduction factor in case 1.

4.2. Tunnel Safety Factor Under Working Case 2

In working case 2, the fluid-solid indirect coupling mode is used to calculate the influence of groundwater seepage on the safety factor of the tunnel. The specific calculation process is as follows: firstly, the seepage mode is turned on, and the mechanical process is closed, and the seepage field change caused by tunnel excavation is analyzed. After the calculation of seepage field is completed, the seepage mode is closed, and the fluid modulus is set to 0 (to avoid the change of the pore water pressure caused by the mechanical calculation), and the mechanical process is started to perform the mechanical calculation until convergence. Using this calculation mode, the pore pressure field is not coupled with the stress field and is an approximate calculation method for calculating groundwater seepage. The variation curve of the characteristic point displacement of the tunnel with the reduction factor under this condition is shown in Figure 6. Comparing Figure 6 with Figure 5, it can be found that the tunnel deformation trend in working case 2 is consistent with working case 1. The settlement of the vault and horizontal displacement are much larger than the deformation of the arch bottom, and the amount of arch bottom uplift is not obvious with the strength reduction factor. When the strength reduction factor is greater than 5.225, the dome settlement and the horizontal displacement of the arch waist increase sharply. The tunnel safety factor calculated in the condition 2 is 5.225.

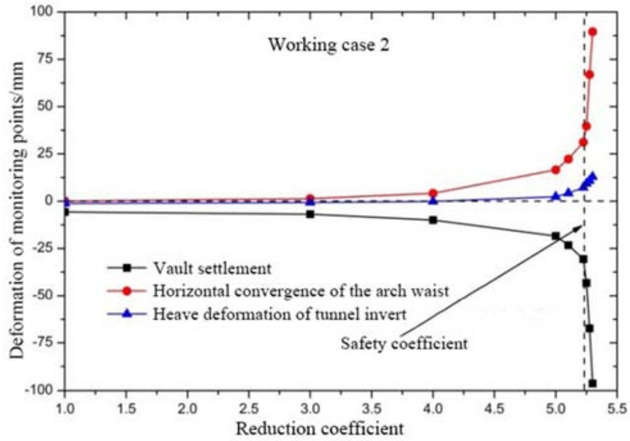

Figure 6. Curves of displacement with reduction factor in case 2.

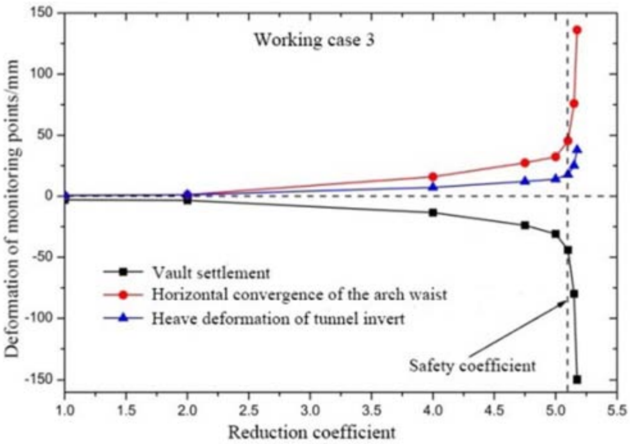

Figure 7. Curves of displacement with reduction factor in case 3.

4.3. Tunnel Safety Factor Under Working Case 3

In working case 3, the direct fluid-solid coupling mode is used to calculate the influence of groundwater seepage on the safety factor of the tunnel. When the fluid-solid coupling model is used to solve the solution, both the fluid mode and the mechanical mode are open, and the fluid-solid coupling is directly solved. In this solution method, each percolation time step contains several mechanical time steps, and the mechanical balance is reached in each percolation time step. In order to ensure the calculation accuracy, the percolation time step is small enough, so it requires a lot of calculation time. The curve of the characteristic point displacement of the tunnel with the reduction factor under this condition is shown in Figure 7. It can be seen from the figure that the vault settlement and the horizontal displacement of the arch waist increase sharply when the strength reduction factor is greater than 5.1, and the tunnel safety factor is 5.1 under this condition.

4.4. Comparison of Calculation Results

In order to study the influence of groundwater seepage and fluid-solid coupling calculation mode on tunnel safety factor. The tunnel safety factors obtained under the three calculation conditions are summarized in Table 3, and the relative changes of the working cases 2 and 3 are calculated based on the calculation result of the working case 1. It can be seen from Table 3 that the tunnel safety factor in working cases 2 and 3 is reduced by 20.2% and 22.1%, respectively, compared with working case 1. It can be seen that groundwater seepage will cause a significant decrease in the safety factor of the tunnel. Comparing the calculation results of working cases 2 and 3, it can be found that the calculation result of working case 3 is slightly smaller than working case 2, which is because the working case 2 adopts the fluid-solid indirect coupling mode, which weakens the interaction between seepage field and stress field. The calculation results of the two calculation modes of working cases 2 and 3 differ only by 1.9%. It can be seen that the fluid-solid coupling calculation mode has no significant effect on the safety factor of the tunnel. However, the calculation process indicates that the calculation time consumed by Case 3 is much larger than Case 2. Therefore, under the condition that the accuracy of calculation result is not significantly affected, it is recommended to use the fluid-solid indirect coupling calculation mode to calculate the safety factor of the tunnel under groundwater seepage.

Table 3. *Safety factor under three different cases.*

Working case	Safety factor	Variation /%
Working case 1	6.55	0
Working case 2	5.225	-20.2
Working case 3	5.1	-22.1

5. Influence of Groundwater Level on Tunnel Safety Factor

The above calculation results show that groundwater seepage has a great influence on the tunnel safety factor. In engineering, the groundwater level often changes, and the variation of groundwater level changes the head difference, which affects the tunnel stability. In order to study the influence of groundwater level on the safety factor of the tunnel, the fluid-solid indirect coupling calculation model is used to calculate the safety factor of the tunnel when the groundwater level is −10, −20, −30, −40 and −50 m. The relationship between the groundwater level and the tunnel position is shown in Figure 8, which is ±0.000 m on the upper surface of the model.

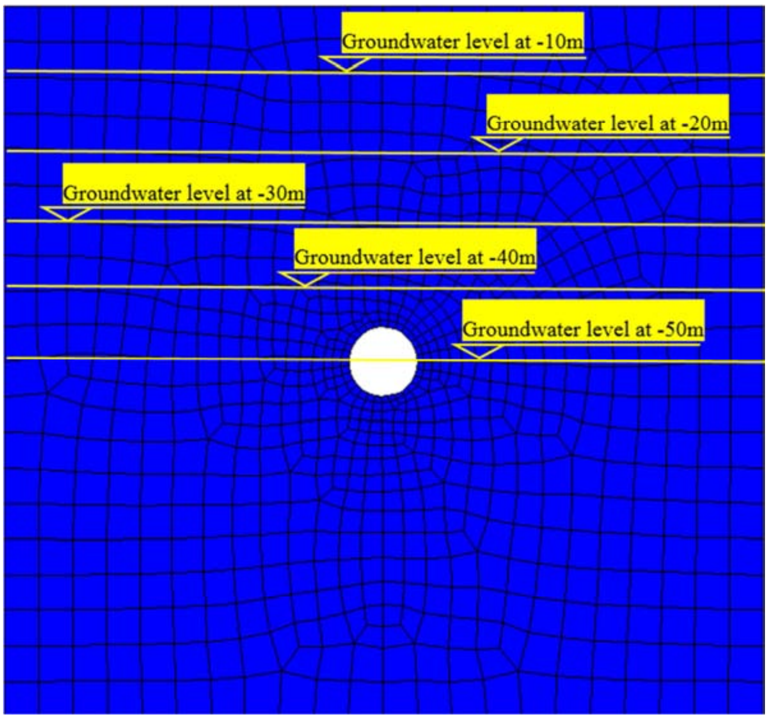

Figure 8. *Relative position between groundwater level and tunnel.*

Figure 9 shows the variation of the tunnel vault settlement with the strength reduction factor for different groundwater levels. It can be seen from the figure that as the groundwater level drops, the tunnel safety factor increases. When the groundwater level is at the upper surface of the model, the tunnel safety factor is the smallest, the value is 5.225; when the groundwater level is −50 m, the tunnel safety factor is the largest, and its value is 6.525. It can be seen from the calculation results in Section 3.1 that the tunnel safety factor is 6.55 when groundwater is not considered. The safety factor of the tunnel is basically same when the groundwater level is −50 m. It can be seen that when the groundwater level is lower than the tunnel dome position, the groundwater seepage has little effect on the tunnel safety factor. In order to reveal the relationship between groundwater level and tunnel safety factor, the tunnel safety factor and the corresponding groundwater level are plotted in Figure 10, and the calculation results are fitted. The calculation results show that the tunnel safety factor is linearly related to the groundwater level. When the groundwater level drops by 10 m, the tunnel safety factor increases by 0.26. Therefore, when tunnel construction is carried out in a water-rich area, the groundwater level should be reduced as much as possible to improve the safety factor of the tunnel without significantly affecting the surrounding environment.

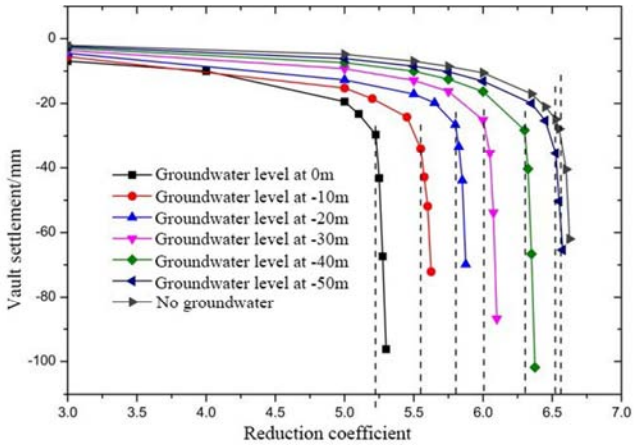

Figure 9. *Safety factor under different groundwater level.*

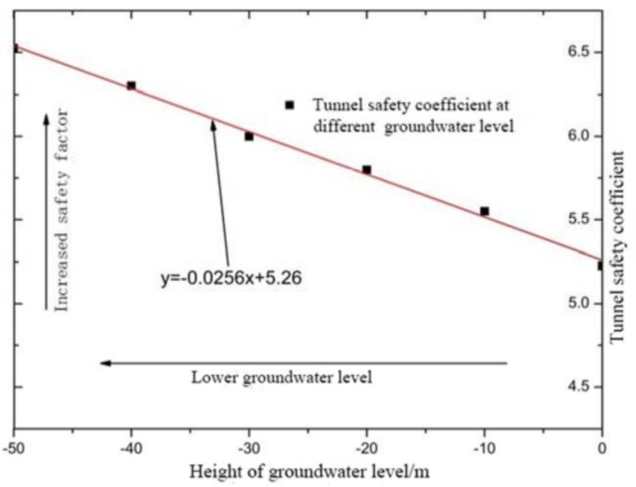

Figure 10. *Curves of safety factor with groundwater level.*

In order to study the variation law of tunnel vault settlement with groundwater level, the fluid-solid indirect coupling model is used to calculate the tunnel vault subsidence with the same safety coefficient and different groundwater levels. The calculation results are shown in Figure 11. It can be seen from Figure 11 that when the reduction factor is the same, the settlement of the vault increases significantly with the increase of groundwater level; and the larger the reduction coefficient, the more significant the increase trend; This is basically consistent with the research conclusions of Li [11] and Li [16]. In tunnel construction, attention should be paid to controlling the increase of surrounding rock deformation caused by groundwater seepage.

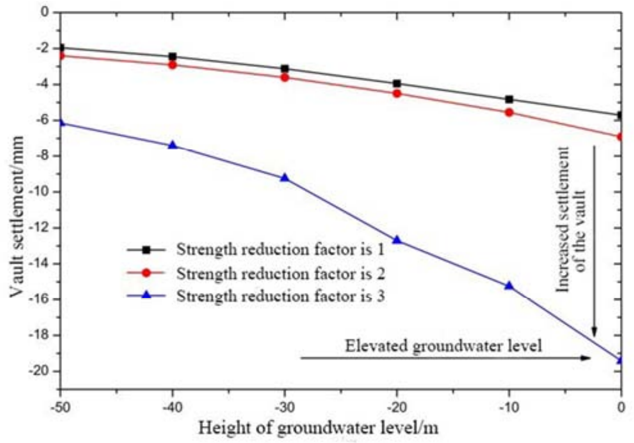

Figure 11. *Curves of crown settlement with groundwater level.*

6. Conclusion

In this paper, three different analysis conditions are established by using the fluid-solid coupling module of FLAC/3D numerical calculation software. Based on the strength reduction method, the sudden change of the displacement of the characteristic points of the tunnel surrounding rock is used as the instability criterion of the tunnel, and the effects of different working conditions and different water levels on the safety factor of the tunnel are analyzed. The result shows that the failure modes and potential sliding surfaces calculated by strength reduction method considering fluid-solid coupling are basically consistent with those obtained by Zheng et al. through indoor geotechnical tests. The strength reduction method based on fluid-solid coupling can be used to solve the safety factor and potential sliding surface of tunnel under groundwater seepage. In the case of groundwater seepage, the safety factor of the tunnel is reduced by about 20% compared with that when the groundwater is not taken into account. The adverse effect of groundwater seepage on tunnel stability should be considered in tunnel design and construction. The calculation results of fluid-solid indirect coupling mode and direct fluid-solid coupling mode are basically same, while the calculation time of fluid-solid indirect coupling mode consumption is much smaller than that of direct fluid-solid coupling mode. It is suggested to use fluid-solid indirect coupling mode to calculate the safety factor of tunnel under groundwater seepage. The deformation of surrounding rock of tunnel increases with the increase of groundwater level, while the safety factor decreases with the increase of groundwater level, and the two are linearly related. For every 10 m increase in groundwater level, the tunnel safety factor decreased by 0.26. In the process of tunnel construction in the rich water zone, the groundwater level should be reduced as much as possible to improve the safety factor of the tunnel.

Acknowledgements

This research is funded by the Natural Foundation of China (no. 51578091).

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