

## Research on seepage-stress coupling analyses of shallow buried and dug vertical overlapping tunnels

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### ABSTRACT

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*vertical overlapping tunnel, seepage-stress coupling, shallow burying, coefficient of permeability*

Groundwater is a common problem in the design and construction of underground structures in water-rich strata. In order to explore the influence of groundwater on the shallow buried excavation of double-cavern vertical overlapping tunnels, this study first reveals the essence of the seepage-stress coupling and the change of the permeability coefficient during the coupling process, assigns the dynamic permeability coefficient to the soil element. Based on the actual seepage coupling analysis, simulates the seepage-stress coupling process with the double-cavern overlapping tunnels by shallow buried excavation in the Guomao-Laojie section, 3C tender section of Shenzhen metro as the project background, and analyzes and verifies the influences of seepage-stress coupling on the deformation characteristics of surrounding rock and pore water pressure during the excavation of overlapping tunnels. Studies have shown that the impact of seepage-stress coupling cannot be ignored during the excavation of double-cavern overlapping tunnels in the case of upper soft and lower hard strata. In order to reduce the amount of surface settlement, the necessary support is required before the excavation of the upward tunnel. Excavation is the main factor for the increase of tunnel deformation. After excavation, the stress concentration will occur in the vicinity of the tunnel vault, floor and left and right side walls. This method can provide reference for hydraulic coupling simulation and analysis of similar projects.

## 1. INTRODUCTION

With the rapid development of urban subway, the development scale of urban underground space is constantly expanding. In order to meet the restrictions of urban construction and the need for comprehensive development and utilization of underground space, vertical overlapping subway tunnels are increasingly used in practical projects owing to their good economic benefits and their ability to adapt to special construction conditions.

At present, shallow buried excavation is not commonly seen in the construction of overlapping tunnels in the world. In China, some tunnels are partially overlapping, such as the intersection of Fuzhou-Xiamen Expressway and Quanzhou-Xiamen Expressway. Shenzhen Metro's Guomao-Laojie Section of 3A and 3C tender section has adopted the layout of the shallow-buried double-cavern vertical overlapping tunnels for the first time in China. In the construction of overlapping tunnels, benching tunneling method is mainly adopted, during which the surrounding rocks easily become loose and unstable due to frequent disturbances. In addition, there are adverse geological conditions (high ground stress, groundwater, geothermal, etc.), structural sections, topographic conditions and other factors, wherein the groundwater is a key problem plaguing the tunnel construction. There are complex interactive coupling between surrounding rock, supporting structures and groundwater in tunnels. Groundwater exists in the rock mass, affecting the strength and deformation of the rock mass and the stability of the project and the surrounding environment. For the surrounding rock in the waterish

environment, its main structure and surrounding rock are under the joint action of overlying rock mass and high water pressure. The seepage-stress coupling will not only change the strength and internal structure of the rock mass, but also reduce the safety, bringing about greater construction risks and greatly increasing the operating costs [1].

The soil/water coupling theory was firstly proposed by TERZAGHI [2] in 1925 as a one-dimensional consolidation theory of soil, and then generalized by BIOT [3-4] to three-dimensional condition theory. Recent years, Many scholars have made some achievements in the studies on double-cavern overlapping tunnels and their construction under fluid-solid coupling action. For example, Li Decai et al. [5] study the design and construction techniques of overlapping tunnels of Shenzhen metro using FEM numerical analysis and field monitoring methods. The study shows that the surface settlement is not only related to the condition of the surrounding rock, but also related to the shape of the cavern. Under the same surrounding rock conditions, the overlapping tunnel has the largest surface settlement, followed by the single-cavern double-layer tunnel, and the parallel tunnel has the smallest surface settlement. Li Jianbo et al. [6] discuss the influence of groundwater flow on the stability of soft rock subway tunnels and the lining support based on fluid-solid coupling theory. The study of Zhao Dongping et al. [7] concludes that under the geological conditions of Shenzhen metro, when the upper and lower tunnels completely overlap with a net distance greater than 3.0D or the two tunnels are completely parallel with a net distance greater than 1.5D, they have little influence on each other, thus the influence is

negligible. The studies of Addenbrooke et al. [8] have shown that the effect of overlapping tunnels is not a simple superposition of the effects of single tunnels. The relative position and spacing of tunnel have great influence on the shape of land settlement curve caused by the tunnel constructed later, while little influence on that of the tunnel constructed first, due to the long construction time. These studies have analyzed and studied construction mechanical behaviors of overlapping tunnels, but fail to consider the seepage-stress coupling effect during the excavation of double-cavern vertical overlapping tunnels, thus the analysis is not comprehensive enough. Therefore, this study combines the numerical simulation and field monitoring to analyze the deformation characteristics of the surrounding rock during the excavation of the double-cavern vertical overlapping tunnels under the action of seepage-stress coupling.

Based on this, this paper intends to establish a coupling model for numerical analysis of seepage-stress coupling problems in excavation of vertically overlapping tunnels. Using the relation between permeability coefficient and stress strain and the secondary development of FISH language of FLAC3D, and combining with seepage-stress coupling algorithm, this study takes the Guomao-Laojie section tunnel of 3C tender section of Shenzhen Metro as an example to realize the simulation of the seepage-stress coupling process and compares it with the measured results, which provides reference for similar tunnel construction.

## 2. BASIC THEORIES

### 2.1 Expression of seepage-stress coupling

In geotechnical engineering, the seepage-stress coupling refers to the physical process of the interaction between the mechanical process and the characteristics of the seepage process in the soil and rock [9]. The coupling problems can be divided into direct coupling and indirect coupling. The former refers to coupling by the action of pore volume, that is, it appears in the interaction between deformed rock and pore fluid. Indirect coupling means the coupling by changing the material characteristics, which is embodied as the coupling of stress field and seepage field caused by hydraulic characteristic change caused by action stress or the coupling of seepage field and stress field caused by material characteristic change caused by fluid pressure change, as shown in Figure 1.

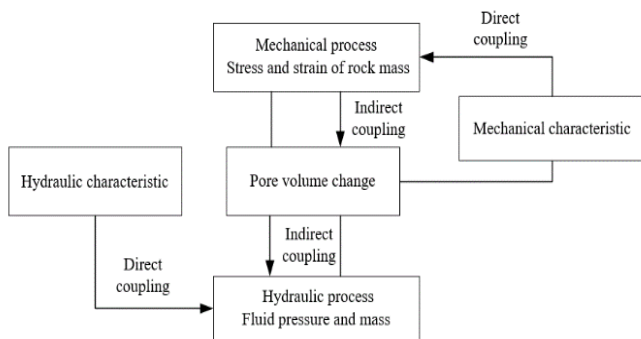


Figure 1. Seepage-stress coupling process

In fact, the seepage force generated by seepage is acting on the stress field of soil in the form of volume force so as to change the strain field and the pores of the soil, and the change in the permeability coefficient of the soil eventually affects the seepage field. That is, the stress field and the seepage field are coupled with each other, and the permeability coefficient is the "bridge" of the coupling of the stress field and the seepage field, and it is also the key to realize the real seepage coupling analysis.

### 2.2 Constitutive equation

When FLAC3D is used to solve the seepage-stress coupling problem, the rock and soil mass are regarded as porous media. The fluid flow in porous media is based on Darcy's law, and the seepage-stress coupling process satisfies Biot equation [10]. When the fluid flows in porous media, it mainly causes the change in pore water pressure, saturation state and seepage discharge. These variables describe the fluid flow through the relationship between the equilibrium equation of fluid particles and Darcy's law. The constitutive equation mainly expresses the relationship between pore pressure, saturation state and volume strain, thus to realize fluid-solid coupling.

For small deformations, the fluid particle equilibrium equation is:

$$-q_{i,i} + q_v = \frac{\partial \zeta}{\partial t} \quad (1)$$

where,  $q_i$  is the seepage velocity,  $q_v$  is the strength of the fluid source of the measured volume and  $\zeta$  is the volume change of the fluid per unit volume of the porous media.

$$\frac{\partial \zeta}{\partial t} = \frac{1}{M} \frac{\partial p}{\partial t} + \alpha \frac{\partial \varepsilon}{\partial t} - \beta \frac{\partial T}{\partial t} \quad (2)$$

where,  $M$  is the Biot modulus,  $P$  is the pore pressure,  $\alpha$  is the Biot coefficient,  $\varepsilon$  is the volumetric strain,  $T$  is the temperature, and  $\beta$  is the coefficient of thermal expansion considering fluid and particles.

The movement of a fluid is described by Darcy's law. For the case where the densities of homogeneous, isotropic solids and fluids are constant, the equation is:

$$q_i = -k[p - \rho_f x_j g_j] \quad (3)$$

where,  $k$  is the permeability coefficient of the medium,  $\rho_f$  is the density of the fluid,  $g_j$  ( $j = 1,2,3$ ) are the three components of the gravitational acceleration.

Changes in the volumetric strain cause changes in the pore pressure of the fluid. Conversely, changes in pore pressure can also lead to volumetric strains. The incremental form of the constitutive equation for porous media is

$$\Delta \tilde{\sigma}_{ij} + \alpha \Delta p \delta_{ij} = H_{ij}(\sigma_{ij}, \Delta \varepsilon_{ij}) \quad (4)$$

where,  $\Delta \tilde{\sigma}_{ij}$  is the stress increment,  $H_{ij}$  is the given function, and  $\varepsilon_{ij}$  is the total strain.

The relationship between strain rate and velocity gradient is

$$\dot{\varepsilon}_{ij} = (v_{i,j} + v_{j,i})/2 \quad (5)$$

where,  $v_j$  is the velocity of a point in a medium.

The boundary conditions used in this paper are the given pore water pressure, the given flow velocity vector outside the normal direction of the boundary and the impermeable boundary.

### 2.3 Change of permeability coefficient in seepage-stress coupling process

Pusch [11] studies the change of hydraulic conductivity during tunnel excavation and holds that it is inaccurate to treat the permeability coefficient as a constant when the seepage field is coupled with the stress field. In the process of simulating seepage flow by FLAC3D, the permeability coefficient of the default unit is constant [10], but the variation of permeability coefficient can be realized by secondary development of FISH. The permeability of rock is closely related to the state of stress and strain. Before the rock enters the yielding stage, that is, the elastic stage, the permeability coefficient will remain at a lower level. Once the rock enters the yielding stage, the permeability coefficient of the rock will be much larger than that of the elastic stage, and there is a sudden jump in permeability coefficient after rock rupture [1]. The empirical formula shows that the body strain can better change the permeability coefficient during the yielding, softening, and failure of the reaction element. Kozeny-Caman [12] establishes the relationship formula between permeability coefficient and porosity of soil, based on which the relationship formula between permeability coefficient and volumetric strain is established as follows:

$$K = k_0 \frac{(1 + \varepsilon_v / n_0)^3}{1 + \varepsilon_v} \quad (6)$$

where,  $k_0$  is the initial permeability coefficient,  $n_0$  is the porosity, and  $\varepsilon_v$  is the strain.

Strain-permeability equation is a regular equation for the change of permeability coefficient of rock in the process of stress. The equation is not only simple in expression form and definite in parameters, but also easy to be realized in FLAC3D, which can also be used for programming the FISH. The permeability coefficients of the elements in different states are calculated according to equation (6), and the element permeability parameters are updated and assigned to each element.

## 3. PROJECT EXAMPLES

### 3.1 Project overview

The cross-section of the vertical overlapping tunnels by shallow buried excavation in the Guomao-Laojie section, 3C tender section of Shenzhen Metro is 6.8 meters in width and 13.2 meters in height. The depth of the tunnel vault is 12 to 16 meters from the surface, which is below the underground water level. The section of the YSK (ZSK)2+388.35~YSK(ZSK)2+430 belongs to the double-cavern vertical overlapping tunnels with a total length of 41.65m. Since the metro is located in a complex urban environment, such as the old town of the bustling business center and the busy traffic section, and the construction site passes through the pile foundation of the building, and the soft and hard soil layers

fluctuate along the line. Therefore, the shallow buried method is chosen for construction. The pre-support of tunnel adopts small conduit grouting; the initial support is net-sprayed concrete and grid steel frame, and the second lining adopts formwork concrete lining support [13-14]. The benching tunneling method is adopted for construction of tunnel. The subway tunnel mainly passes through the Quaternary residual layer and the granite full weathering zone. The overlying strata of the tunnel are weakly broken and rich in water, and the stability during construction is poor. So the surrounding rock is "upper soft and lower hard," in which the surrounding rock of the upper cave mainly belongs to grade IV, and the surrounding rock of the lower cave mainly belongs to grade II [15].

### 3.2 Model building

The tunnel model is built by FLAC3D software, with a size of 100 m × 100 m × 40 m, and the vertical distance between the two tunnels is 2.3 m. The model produces a total of 77,729 nodes, 116,366 units, and the numerical model is shown in Figure 2. The boundary conditions of the model are as follows: the four sides and the bottom of the model are used as displacement boundaries, and the four sides are restricted from horizontal movement, and the bottom is restricted from vertical movement, and the upper boundary of the model is used as a free boundary. The four sides and the ground of the model are defined as permeable boundaries. In the model, the buried depth of groundwater level is defined as 2.4 m. In the FLAC3D software, the unstable fluid flow is used for numerical simulation calculation. The formation damage model uses the Moore-Coulomb model. The initial lining and the second lining are defined as solid elements, and the anchor rod is defined as the cable element.

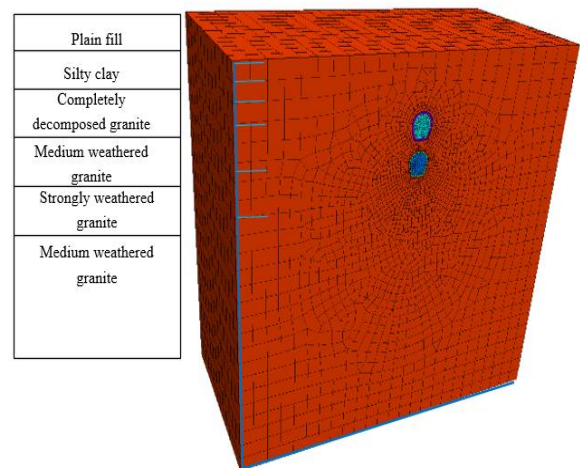


Figure 2. Calculation model

### 3.3 Calculation parameters

According to the data of geological exploration, the stratum parameters and support parameters of the selected numerical model are shown in Table 2.

**Table 2.** Stratum and support parameters of model

Materials	Bulk modulus K/MPa	Shear modulus G/MPa	$\rho$ kg/m <sup>3</sup>	Poisson ratio $\mu$	Cohesion C/MPa	Internal friction angle $\Phi(^{\circ})$
Plain fill	18.9	6.3	1970	0.30	0.309	24.6
Silty clay	10.9	8	1910	0.35	0.200	25.0
Gravel layer	20	11.8	1950	0.3	0.228	26.8
Completely decomposed granite	13.9	10.4	1950	0.35	0.158	25.1
Strongly weathered granite	30.4	21.9	2040	0.35	0.241	25
Medium weathered granite	83.3	62.5	2000	0.35	0.6	25
Initial support	15.56×10 <sup>3</sup>	11.67×10 <sup>3</sup>	2500	0.2	—	—
Secondary lining	2×10 <sup>3</sup>	1.52×10 <sup>3</sup>	2500	0.2	—	—

**3.4 Simulated excavation procedure**

The overlapping tunnel of this section is constructed by the short benching tunneling method, with the upper step driving 12 meters and the lower step driving 6 meters. In the calculation, 10 construction steps were simulated as follows: Prior to excavation, pre-reinforcement of arches is carried out. 1) Excavate the surrounding rock in the upper half of the lower cavern; 2) Conduct initial support for lower cavern arch; 3) Excavate the surrounding rock in the lower half of the lower cavern; 4) Conduct initial support for lower half of the lower cavern; 5) Conduct water-proof layer and secondary lining for the lower cavern; 6) Excavate the surrounding rock of the upper half of the upper cavern; 7) Conduct initial support for the upper cavern arch; 8) Excavate the lower half of the lower cavern; 9) Conduct initial support for lower half of the upper cavern; 10) Conduct water-proof layer and secondary lining for the upper cavern.

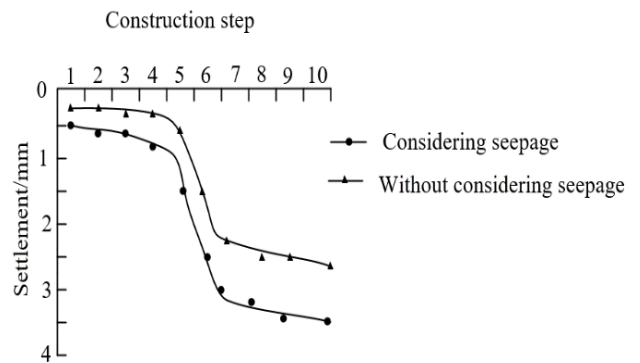
**4. ANALYSIS OF CALCULATION RESULTS**

**4.1 Analysis of surface settlement**

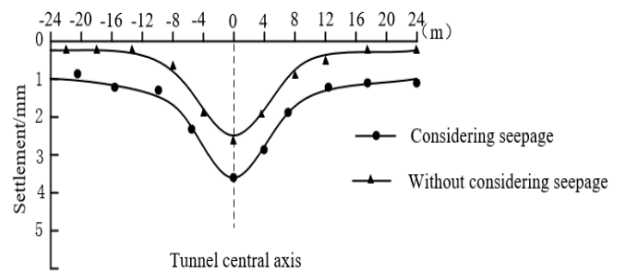
As can be seen from Figure 3, the maximum settlement of each construction step varies with the change of construction step, regardless of whether seepage is taken into account or not. In the construction of the lower tunnel, the surface settlement is relatively stable, and the excavation of the upper arches has a greater impact on the surface settlement. The subsequent construction steps have a smaller impact on the surface settlement. The settling amount considering the seepage is 1.5mm larger than that without considering the seepage. Due to the supporting work done during tunnel excavation, the maximum surface settlement is only 3.38 mm, which will not cause adverse effects on the surface buildings. The fitting curve of the lateral surface settlement value of the tunnel is a Gaussian regression curve (see Figure 4), suggesting that the surface settlement caused by the shallow buried excavation of overlapping tunnels in the water-rich soft surrounding rock is in accordance with the basic law of the formation deformation caused by the general tunnel construction.

Compared with the surface settlement under the condition of no or no seepage, the maximum settlement value caused by tunnel construction without seepage is smaller than the maximum settlement value caused by tunnel construction under seepage. On the one hand, due to the creep effect caused by seepage, from the tunnel excavation to the surrounding rock is basically stable, the soil continues to settle with time; on the other hand, with the excavation of the tunnel, the soil around the tunnel is obtained after the peak of the construction

disturbance. When compacted, the pore pressure of the overlying soil layer gradually decreases, the permeability coefficient decreases, the head decreases, and the soil settles and settles, causing large settlement on the surface.



**Figure 3.** Surface settlement with construction steps



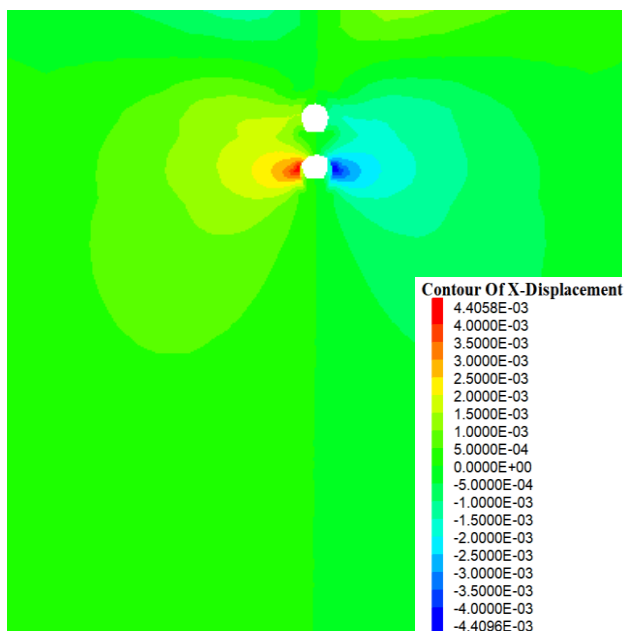
**Figure 4.** Tunnel lateral surface settlement value

Table 3 shows the final settlement values of 5 representative monitoring points with different calculation methods, in which the settlement value without considering ground water has the largest difference from the measured settlement value, followed by the settlement value of seepage-stress coupling without consideration of permeability variations, and the settlement value of seepage-stress coupling with consideration of permeability variations is the closest to the measured settlement value. The settlement value considering the coupling effect of seepage-stress is much higher than the settlement value calculated by the separate mechanics. The final settlement considering the permeability variation mode is also slightly larger than the mode where the permeability does not change. Therefore, the influence of groundwater cannot be ignored and it is more realistic to consider the permeability variations, which shall be worthy of attention in the excavation simulation of tunnels in upper soft and lower hard soil.

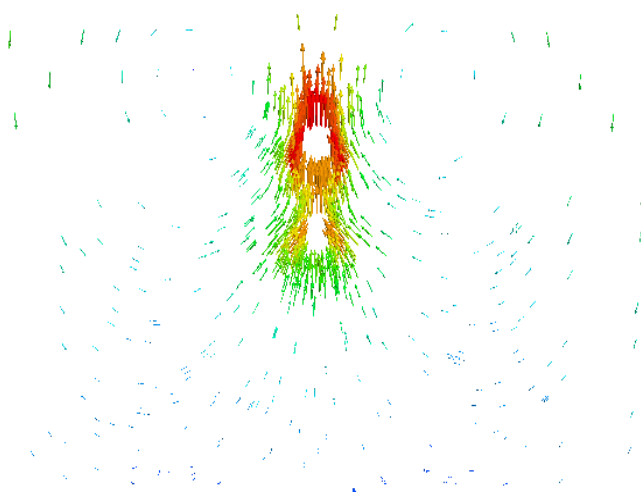
**Table 3.** Final settlement values of monitoring points with different calculation methods

Monitoring points	Mechanical calculated values /mm (without seepage)	seepage-stress coupling/mm		Measured settlement value/mm
		Without seepage variation	With seepage variation	
1	-2.85	-3.02	-3.41	-3.32
2	-2.53	-3.01	-3.28	-3.24
3	-2.66	-2.98	-3.20	-3.25
4	-2.78	-2.86	-3.28	-3.27
5	-2.92	-2.90	-3.32	-3.23

**4.2 Deformation analysis of surrounding rock of the tunnel cavern**



**Figure 5.** X-direction displacement

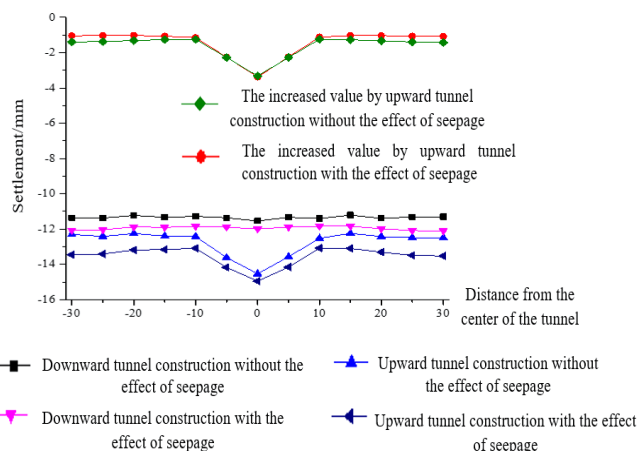


**Figure 6.** Cross-sectional displacement vector

The tunnel is compressed under the pressure of surrounding rock, if the deformation is too large, plastic failure will occur

and the strength will decrease. Therefore, it is necessary to monitor the upper and lower caverns longitudinally in real time, and pay attention to the displacement change during the construction of the newly built upward tunnel in order to take timely protective measures to ensure the smooth progress of the project. Figure 5 shows the displacement of the tunnel cavern periphery in the x direction, and Figure 6 shows the cross-sectional displacement vector, indicating that the soil around the tunnel begins to displace towards the free tunnel surface after the tunnel construction, which is specifically shown as the settlement of the tunnel vault, the uplift of the arch bottom, and the extrusion of the soil on both sides to the center of the tunnel.

As shown in Figure 7, after tunnel construction without seepage, the maximum value of vault settlement is 11.5 mm. The excavation of the upward tunnel disturbs the downward tunnel and causes it to sink. Thus the maximum vault settlement value after construction is 14.5 mm. The vault settlement value is 12 mm after the construction of the existing tunnel under the effect of seepage. The construction of the newly-built tunnels will produce a 3.3 mm settlement value to the vault of the existing tunnel, thus the final settlement value of the existing tunnel vault is 14.8 mm. Through the comparison of the construction simulations with and without seepage, it is found that the difference caused by the seepage to the vault deformation is 0.3 mm. The deformation of vault is small under the effect of seepage, and excavation is the most important cause of vault deformation and settlement in existing tunnels.



**Figure 7.** Vault settlement of the tunnels

As shown in Figures 8 and 9, as the tunnel is squeezed by surrounding rock, and arch bottom is uplifted. The average of the arch bottom uplift of the downward tunnel without seepage is 4 mm. Due to the excavation of the upward tunnel, the stress of the stratum above the downward tunnel is released, which has little influence on the downward tunnel arch bottom. The arch bottom uplift of the upward tunnel is larger with the maximum of 7.7 mm and 6.9 mm, respectively. Through the comparison of the arch bottom uplift values of tunnels with and without seepage, it is found that the difference is minimal, without any obvious changes, which is the same as the above vault analysis results. It is concluded that the seepage has little effect on the self-stability of the tunnel structure. Under the effect of seepage, the tunnel structure itself can maintain high stability.

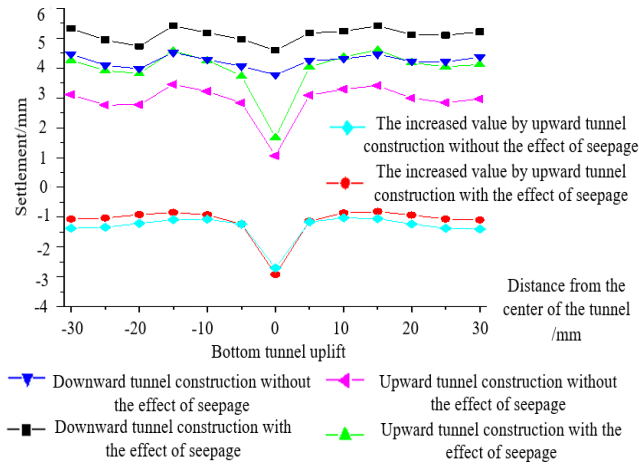


Figure 8. Arch bottom uplift of the downward tunnel

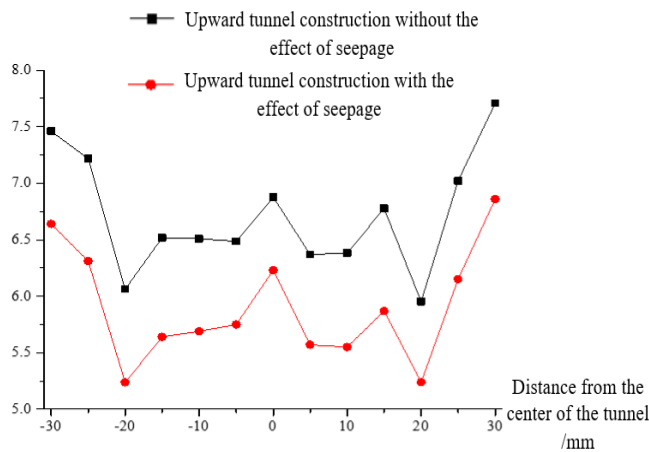


Figure 9. Arch bottom uplift of the upward tunnel

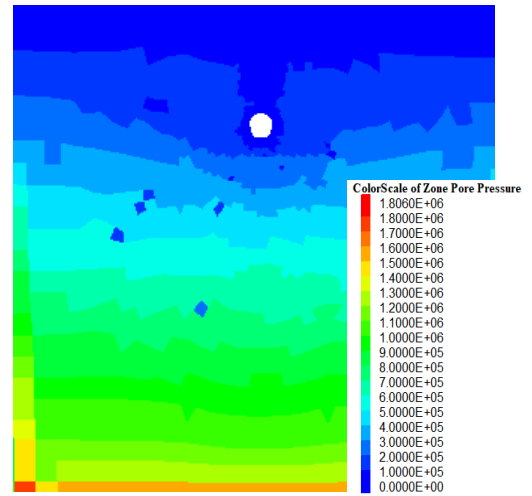


Figure 10. Pore water pressure after downward tunnel construction

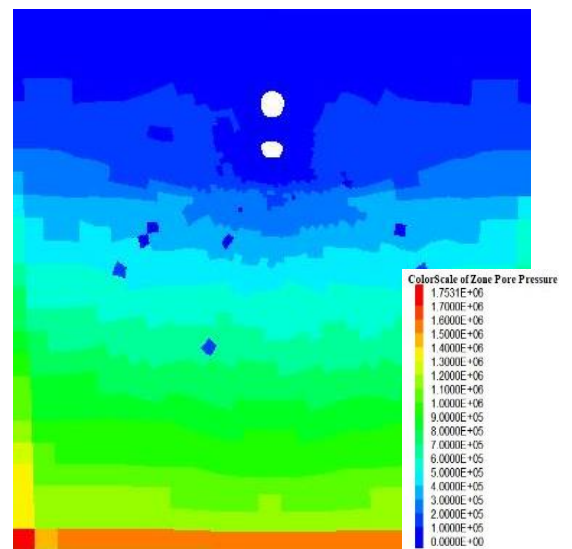


Figure 11. Pore water pressure after construction of newly-built upward tunnel

### 4.3 Pore pressure analysis

The excavation of the caverns brings disturbance to the surrounding rock, causing the secondary distribution of rock stress, and it also affects the distribution of the seepage field after excavation, causing changes in the pore pressure, particularly the pore pressure at the periphery of the cavern. In the case of peripheral drainage, the pore pressure is significantly reduced.

As shown in Figures 10 and 11, after the construction of the downward tunnel, the pore water pressure around the surrounding rock of the tunnel decreases, and the pore water pressure in the surrounding area above the tunnel arch changes drastically. After the newly built upward tunnel is excavated, the pressure of the water head around the downward tunnel is further reduced, and the pore water pressure range extends to the arch bottom. The pore water pressure around the downward tunnel also decreases. A funnel-shaped pore water pressure zone is formed around the tunnel axis boundary, and the hydraulic gradient is large. Under the influence of pressure difference, groundwater flows to the free surface of the tunnel to form a flow water pressure. As the lining is impervious to water or its water permeability is very small, the pore water pressure in the surrounding of the tunnel lining is greater than that in the periphery of the tunnel because of the dual effects of hydrostatic pressure and hydrodynamic pressure.

Because the porosity of rock is the main factor affecting the seepage of rock, so in order to reduce the adverse effect of seepage on the tunnel, the construction of tunnel grouting support shall be advanced to increase the density of rock mass around the tunnel and reduce the porosity. The cement-water glass double slurry is used. The water-cement ratio in the slurry is 1.5:1, the water glass slurry concentration is 36Be', and the CS slurry volume ratio is 1:1. The grouting hole row spacing is 4 m, the grouting hole depth is 4 m, the grouting hole spacing is 2 m, the grouting hole elevation angle is 20°, and the grouting circle range is 6 m. In FLAC3D software, assuming that the slurry injected into the grouting circle is evenly distributed, the grouting operation is numerically simulated by setting the material property parameters and contact surfaces within the grouting circle.

Through numerical simulation, it was found that after the advanced tunnel grouting, a funnel-shaped pore water pressure zone is also formed around the grouting circle boundary of the upward and downward tunnels. The pore water pressure is obviously reduced in the range of the grouting circle, and the pore water pressure is zero under the good grouting conditions. At the same time, because the grouting ring blocks the action of the dynamic water pressure on the tunnel, the pore water

pressure at the edge of the tunnel lining is reduced to the lowest value.

## 5. CONCLUSIONS

With the double-cavern overlapping tunnels by shallow buried excavation in the Guomao-Laojie section, 3C tender section of Shenzhen Metro as the project background, this paper carries out the numerical simulation of seepage-stress hydraulic coupling for double-cavern overlapping tunnels. The results are concluded as follows:

(1) The process of seepage-stress coupling and the constitutive equation are summarized. Based on these, the equation of permeability coefficient with body strain is introduced, and the defect of permeability in FLAC3D seepage simulation is improved. The result is verified to be reasonable.

(2) When the overlapping tunnels are excavated, the surface settlement is mainly caused by the excavation of the upper cavern, and the settlement value of the monitoring point with seepage-stress coupling and considering the permeability variation is larger than the settlement value without considering the seepage, which is relatively more consistent with the measured result. The impact of seepage-stress coupling cannot be ignored during the excavation of double-cavern overlapping tunnels in the case of upper soft and lower hard strata. In order to reduce the amount of surface settlement, the necessary support is required before the excavation of the upward tunnel.

(3) The maximum displacement around the upper and lower caverns of double-cavern overlapping tunnels occurs under the effect of seepage. The displacement value is within the acceptable range, and there is very little difference from that without the effect of seepage. It is concluded that excavation is the main factor increasing tunnel deformation. Under the effect of seepage, the tunnel structure itself can maintain high stability.

(4) Tunnel excavation has great influence on the surrounding groundwater, resulting in sharp decrease of pore water pressure and drop of water head in the surrounding rock, forming a funnel-shaped pore water pressure zone around the tunnel. Groundwater creates dynamic water pressure at the boundary of the lining under the effect of pressure difference, and the tunnel lining edge has greater pore water pressure around the tunnel under the double effects of hydrostatic pressure and hydrodynamic pressure. Combining numerical simulation results and experimental results in the laboratory, it is concluded that the advanced grouting of the tunnel will help reduce the pore water pressure around the tunnel and reduce the impact of groundwater on the tunnel.

## ACKNOWLEDGMENT

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## NOMENCLATURE

$q_i$	the seepage velocity
$q_v$	the strength of the fluid source of the measured volume
$M$	the Biot modulus
$P$	the pore pressure
$T$	the temperature
$k$	the permeability coefficient of the medium

$g_j$  components of the gravitational acceleration  
 $H_{ij}$  the given function  
 $v_j$  velocity of a point in a medium  
 $k_0$  the initial permeability coefficient  
 $n_0$  the porosity

**Greek symbols**

$\zeta$  the volume change of the fluid per unit volume of the porous media

$\alpha$  the Biot coefficient  
 $\varepsilon$  the volumetric strain  
 $\rho_f$  the density of the fluid  
 $\beta$  the coefficient of thermal expansion considering fluid and particles.  
 $\Delta\tilde{\sigma}_{ij}$  the stress increment  
 $\varepsilon_{ij}$  the total strain  
 $\varepsilon_v$  the strain