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Research of influence on tunnel crossing neighboring reservoir in Niuheling mutated rock mountain area

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Abstract: *Mountain tunnels crossing neighboring reservoirs will have important effects on the structural safety of reservoirs. In this paper, based on the Niuheling mountain tunnel project, the impact of a mountain tunnel crossing a reservoir near a mutated strata on the reservoir above and the tunnel surrounding rock is analyzed by using finite element numerical simulation. The results show that tunneling under the reservoir will lead to the settlement of the reservoir, and the settlement value increases with the increase of tunnel depth and reservoir water level. The properties of the mutated rock layer near the tunnel have an important influence on the extension of the surrounding rock deformation. When the elastic modulus of the mutated rock layer is small, the mutated rock layer will prevent the excavation deformation from expanding to the other side of the rock layer. When the elastic modulus of the mutated rock layer is large, the mutated rock layer will expand the influence range of the surrounding rock deformation. When the elastic modulus of the mutated rock layer is small, the greater the thickness of the mutated rock layer, the greater the blocked effect of the rock layer on the deformation of the surrounding rock. When the elastic modulus of the mutated rock layer is large, the blocked effect of the thickness of the mutated rock layer on the deformation of the surrounding rock is not evident. The results of the study can provide some theoretical basis for tunneling with special geology of mutated rock layers and special working conditions such as crossing reservoirs.*

Keywords: *Mountain tunnel; Reservoir; Mutated strata; Deformation influence; Numerical simulation.*

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I. Introduction

The railway plays a pivotal role in Chinese transportation network, and railway construction is in full swing. At the same time, due to the harsh natural conditions in mountainous areas, complex regional geological conditions and construction difficulties, research on the impact of tunnel construction in mountainous areas has received more and more attention from the academic and engineering communities. One of the important conditions is the tunnel crossing under the reservoir, and the complex geological conditions, tunnel excavation is very likely to induce large-scale deformation of the tunnel surrounding rock to affect the construction progress or even cause tunnel collapse, reservoir water backflow or other construction disasters.

At present, the main research methods for tunnel construction-induced ground settlement are empirical method, analytical solution method, numerical simulation method and model test method. In the empirical method, Peck [1], Clough et al. [2], O'Reilly and New [3], Mair et al. [4] and Celestino et al. [5] proposed formulas for the calculation of surface transverse settlement based on a large amount of engineering empirical data. In the analytical solution method, Sagaseta [6] derived the analytical equations for longitudinal settlement and transverse settlement deformation of tunnel excavation under undrained conditions. Lin et al. [7] derived the ground settlement calculation equations for different convergence modes of tunnel boundary soil layers based on virtual mirror technology. Wang et al. [8] introduced the random field theory into the analysis of tunnel ground settlement reliability index. Among the numerical simulation methods, Goh and Zhang [9] used numerical simulation to predict the ground settlement during tunnel boring. Wang and Zou [10] used the nonlinear finite element software ABAQUS to establish a finite element model to obtain the deformation laws of ground settlement, horizontal displacement of strata and stratified settlement under the disturbance of tunnel construction. Zhang et al. [11] used the finite element software ABAQUS was used to simulate the excavation process of different surrounding rocks and made an analysis of tunnel surface settlement, cavern convergence deformation and vault subsidence. In the model test method, Yoshikoshi et al. [12] made a theoretical derivation of the surface settlement caused by tunnel excavation based on a small cavity model, combining field measurements and model tests. Wang and Jin [13] made a model test study of surface settlement and internal soil settlement due to soil loss during the construction of sand shield tunnel by simulating the ground loss through gradual release of soil. Nowadays, numerous theoretical studies have been carried out on ground settlement and surrounding rock deformation caused by tunnel excavation. However, there are fewer theoretical studies related to the impact of tunnel excavation in mountainous areas induced by nearby reservoirs, and most of the existing studies are the analysis of the impact on existing tunnels before and after reservoir storage. Zhao et al. [14] analyzed the safety of the Hengjiang main stream Yanjin-Yangliutan reservoir on nearby tunnels by means of numerical simulation. Hou and Xu [15] proposed the seepage of water from the Lijiahe reservoir to the tunnel in combination with a deep buried highway tunnel project. Chen [16] explored the analysis of water storage on the safety of the tunnel by establishing a finite element numerical model to numerically analyze the stress distribution in the secondary lining of the entrance section of the tunnel before and after reservoir impoundment.

Previous studies have shown that the condition of close crossing of reservoirs by tunnels in mountainous areas with mutated rock formations is seldom studied. Therefore, this paper relies on the proposed tunnel project in Niuheling to establish a 2D finite element model and analyze the impact of factors such as different buried depths, different reservoir water levels and properties of mutated rock layers on the reservoir and tunnel surrounding rocks after tunnel excavation.

II. Engineering introduction

Niuheling tunnel is proposed to be built in Jinyun County, Lishui City, Zhejiang Province, in Hu town. The area is located in many low mountains, the terrain is undulating. Elevation 235-522.4m, relative height difference 10-287.4m, natural slope 25°-60°. There is water in the gullies all year round and the volume of water is large. In some areas it is gathered into reservoirs, and the water level and volume of reservoirs are influenced by the seasons.

In this paper, the tunnel is located near the entrance section, and the proposed scheme crosses the end of the reservoir with a shallow tunnel depth. The topography around the reservoir and the mountain profile around the proposed tunnel are shown in Fig. 1 and Fig. 2, respectively. According to the engineering geological mapping and geological drilling, the stratum lithology of the reservoir crossing section is mainly siltstone and tuff of Tangshang Formation, Upper Cretaceous. As shown in Fig. 2, the surrounding rocks in the area are mainly weathered tuffs with broken rock mass and soft rock quality, and there is a mutated rock layer near the tunnel, which is weathered siltstone, 2.2m thick, soft and broken. The section of the surrounding rock level is V. The tunnel is constructed by the short step method, and the ring excavation is reserved for the core area soil. Firstly, the upper ring guide pit is excavated, timely spraying mix closed rock surface after excavation, and taking support measures. Secondly, lower half section and support is excavated, and then excavating the core area. The core area was excavated and immediately constructed the elevation arch, and finally the second lining of the full section.

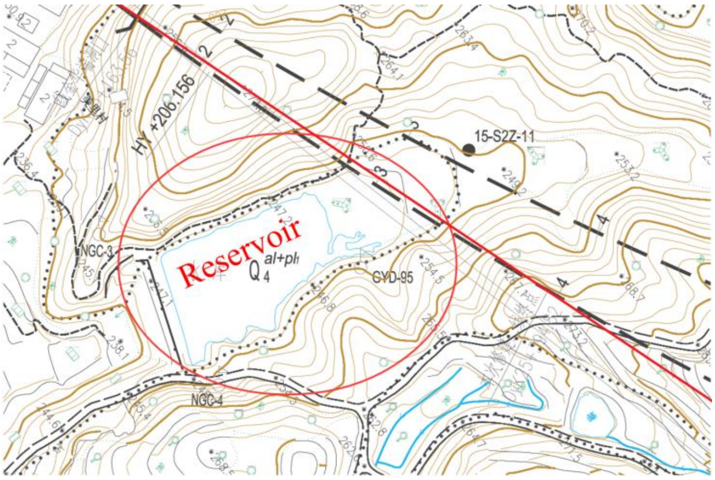


Fig. 1 Topographic map around the reservoir

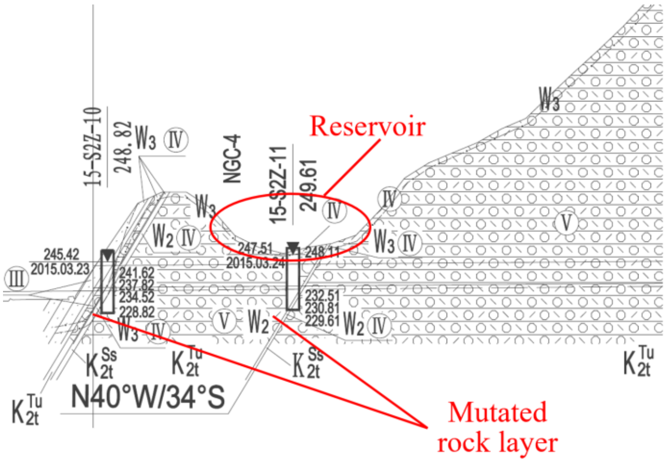


Fig. 2 Geological section view around the tunnel

III. Model introduction

3.1 Establishment of numerical model

In order to study the impact of the construction of a mountain tunnel through a reservoir with mutated rock layers on the reservoir and surrounding rocks, this paper establishes a 2D finite element numerical model based on the geological profile shown in Fig. 2. The model is mainly divided into four parts: the surrounding rock, the mutated rock layer, the equivalent generation layer and the tunnel structure. The base of the surrounding rock is 171 m long, the left side is 30.5 m high, the right side is 95.7 m high, the central terrain is undulating, and the lowest point of the central reservoir is 47.7 m from the bottom of the surrounding rock. According to the original geology, there are two siltstone variant layers in the surrounding rock, the left side variant layer is 2.9 m thick, and the right side layer is 2.2 m thick. The tunnel adopts a three-centered circle with an inverted arch tunnel, with R_1=3.5 m, A_1=60 °, R_2=8m, A_2=55°, R_3=10m, A_3=0° determined. The lining is 70 cm thick. The role of anchors is mainly to improve the cohesion and internal friction angle of the surrounding rock, forming a new composite with the surrounding rock. Therefore, the role of anchors can be replaced by the equivalent of the 1m thick equivalent generation layer in this model. The model is shown in Fig. 3.

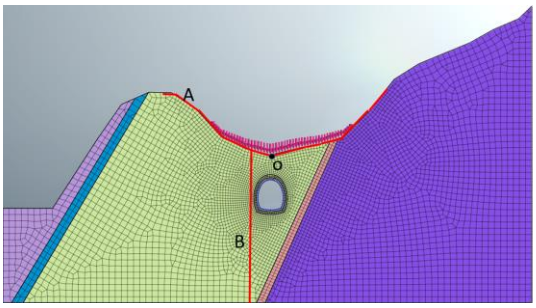


Fig. 3 Numerical model of tunnel crossing reservoir

The Mohr Coulomb model was used to simulate the constitutive relationships of the surrounding rock, mutated rock layers, and equivalent layers in the numerical model, defined as isotropic materials with 2D plane strain elements as their attributes. The lining is an elastic element with isotropic properties and is a 2D plane element. When dividing the grid, in order to ensure the quality of the grid, the grid size of the soil around the tunnel is set to 0.5 m, the grid size of the rock mass around the reservoir bottom and the mutated rock layer close to the tunnel is set to 1 m, and the grid size of the other rock masses is set to 2 m. After discretization, the model has 5487 nodes and 5421 elements. The physical parameters involved in the model are shown in Table 1.

Table 1 Physic-mechanical parameters for numerical analyses

Rock Type	Unit weight /kPa	Elastic modulus /MPa	Poisson’s ratio	Cohesive force /kPa	Internal friction angle /Deg
Weathered tuff	26	1000	0.35	200	40
Mutated rock	25	700	0.28	180	38
Equivalent layer	23	2500	0.3	500	43
Lining	24	24000	0.23	-	-

The water pressure in the model is calculated and applied to various nodes on the bottom of the reservoir with an equivalent concentrated force. The simulation of tunnel excavation first activates the rock mass, mutated rock layers, water pressure, gravity, and boundary conditions before excavation, with initial displacement reset to zero. Then the rock mass in the tunnel is passivated. Finally, the rock mass in the lining and equivalent layers is passivated and activated.

3.2 Setting of numerical working conditions

In numerical simulation analysis, four tunnel buried depths of 4m, 8m, 12m and 16m were set, and four reservoir water levels of 0m, 5m, 10 m and 15m were set. After combination, a total of 16 working conditions were used to explore the impact of tunnel excavation on the reservoir and surrounding rock at different water levels and buried depths.

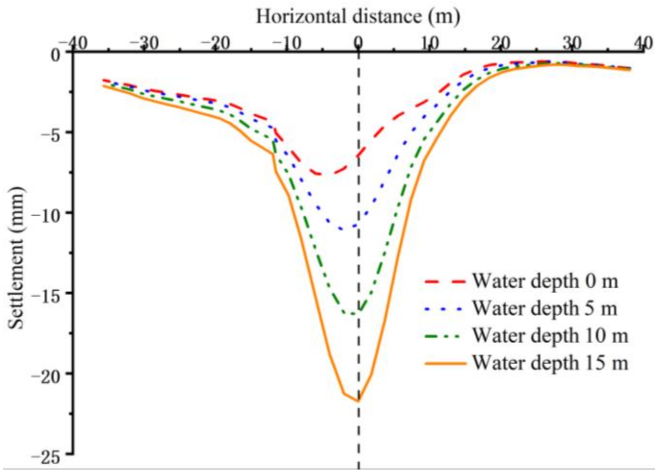
In addition, in order to explore the influence of mutated rock properties near the tunnel, this study sets up four mutated rock conditions for the working conditions of buried depth of 8 m and reservoir water level of 10 m. The four elastic modulus are 7 MPa, 70 MPa, 700 MPa and 7000 MPa, respectively. The influence of mutated rock thickness on surrounding rock deformation is compared and analyzed when the elastic modulus is lower at 70 MPa and higher at 7000 MPa, and the set rock thickness includes 1 m, 2.2 m (actual thickness) and 4 m.

IV. Analysis of numerical simulation results

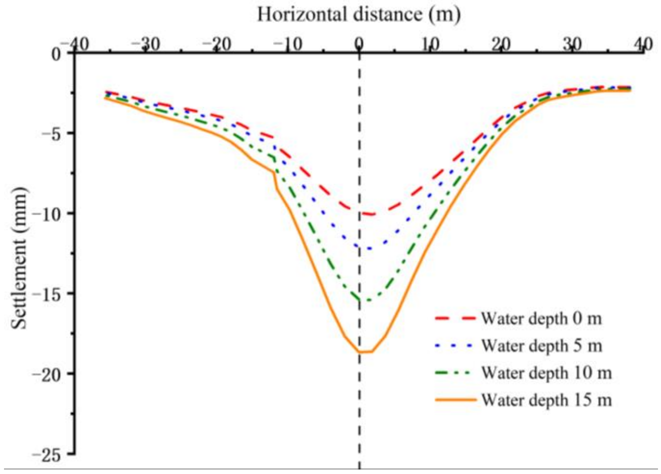
The established finite element model simulates the impact of tunnel excavation with different buried depths on the reservoir and surrounding rock, and considers four types of reservoir water levels to analyze the impact of tunnel excavation at different buried depths and water levels. This study obtains the settlement amount of node A on the bottom curve of the reservoir in Fig. 3, plots the settlement amount curve of the reservoir bottom surface. The horizontal displacement of node B on the straight line 8 m to the left of the tunnel arch crown is obtained, and the horizontal displacement curve on the left side of the tunnel is plotted.

4.1 Reservoir bottom settlement

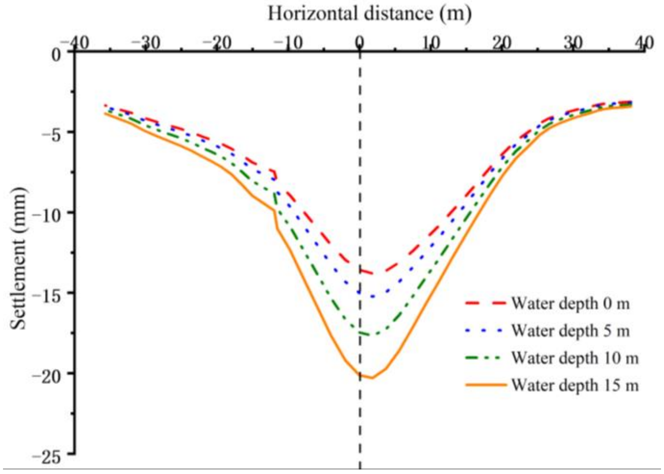
By controlling the buried depth of the tunnel and the depth of the reservoir, the settlement curve of the reservoir bottom at the same buried depth and different water levels, as well as the settlement curve of the reservoir bottom at the same water level and different buried depths, are obtained, as shown in Fig. 4 and Fig. 5. It can be seen that the settlement of the reservoir bottom after tunnel excavation presents a groove shape, with the largest settlement directly above the tunnel from Fig. 4. The further the horizontal distance from the tunnel, the smaller the settlement of the reservoir bottom.



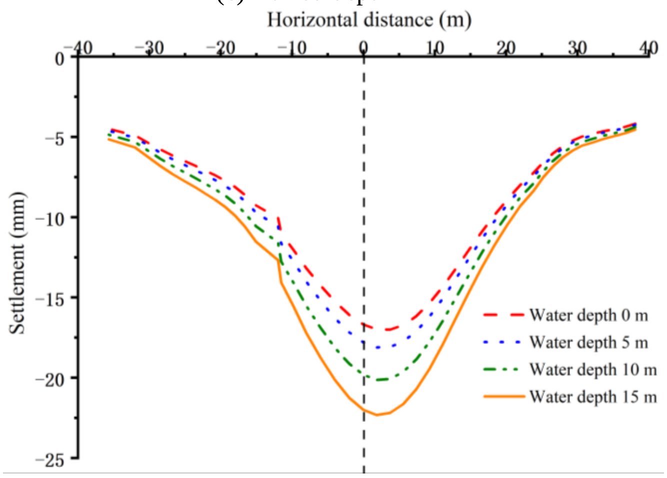
(a) Buried depth 4 m



(b) Buried depth 8 m



(c) Buried depth 12 m



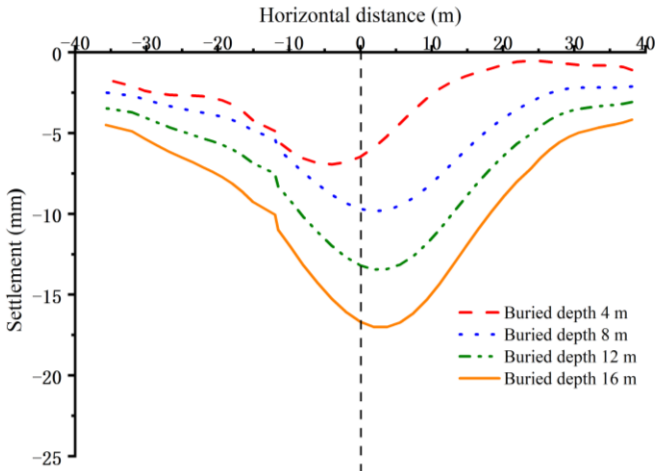
(d) Buried depth 16 m

Fig. 4 Settlement of reservoir bottom surface at different water levels

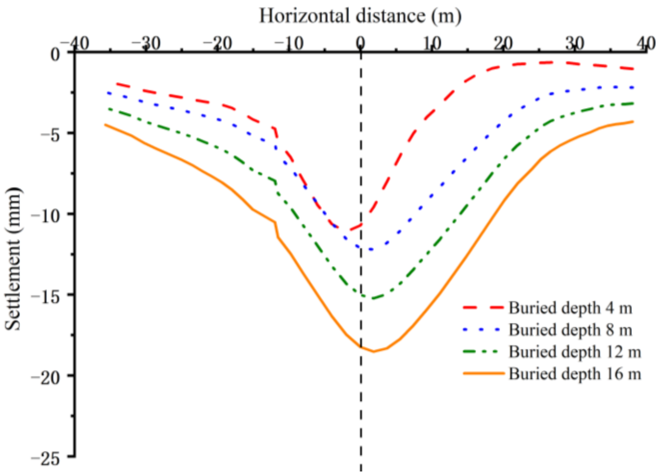
When the tunnel is buried at a certain depth, the settlement of the reservoir bottom is shown in Fig. 4. When the tunnel is buried at a certain depth, the settlement of the reservoir bottom increases with the increase of the reservoir water level. When the tunnel is buried at a depth of 4 m and there is no water pressure in the upper part, the settlement at the lowest point of the reservoir is 6.5 mm. As the water level increases, when the water level in the reservoir is 15 m, the settlement at the lowest point of the reservoir is 24.1 mm, which is 17.6 mm higher than that under anhydrous pressure, with an increase of 270.8%. The buried depth of the tunnel is 8 m. When there is no water pressure at the upper part, the settlement at the lowest point of the reservoir is 10.3 mm. When the reservoir water level is 15 m, the reservoir water level is 19.4 mm, and the settlement increases by 9.1

mm, with an increase of 88%. The buried depth of the tunnel is 12m. When there is no water pressure on the upper part, the lowest point settlement of the reservoir is 13.7 mm. When the water level is 15 m, the lowest point settlement of the reservoir is 20.6 mm, and the settlement has increased by 6.9 mm, an increase of 50.4%. The buried depth is 16 m. When there is no water pressure above, the settlement at the lowest point of the reservoir is 17.3 mm. When the water level of the reservoir is 15 m, the settlement at the lowest point of the reservoir is 23.0 mm, and the settlement has increased by 5.7 mm, an increase of 32.9%. Therefore, it can be obtained that when the tunnel depth is definite, the settlement of the reservoir bottom increases with the increase of the reservoir water level, but the impact of water level on the settlement of the reservoir bottom will decrease with the increase of tunnel depth.

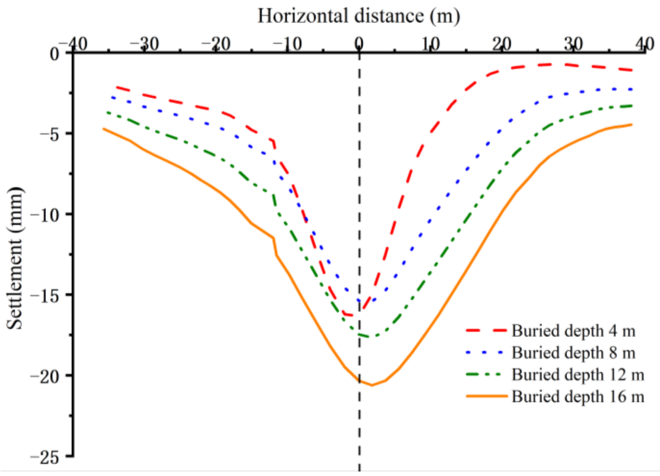
The settlement comparison of tunnels with different buried depths excavated at different reservoir water levels is shown in Fig. 5. When the water level of the reservoir is constant and the water level is shallow, as shown in Fig. 5(a) and (b), the settlement of the reservoir bottom increases with the increase of buried depth. When the water level of the reservoir is deep, as shown in Fig. 5(c) and (d), except for tunnels buried at a depth of 4 m, the settlement of the reservoir bottom caused by other buried tunnels increases with the increase of buried depth. When the tunnel is buried at a depth of 4 m and the water level is 10 m, the maximum settlement of the reservoir bottom exceeds the settlement at a depth of 8 m, which is close to the maximum settlement at a depth of 12 m. As the water level continues to increase, the maximum settlement of the reservoir bottom at a tunnel depth of 4 m exceeds the settlement at a depth of 12 m, approaching the settlement at a depth of 16 m. Therefore, it can be concluded that under appropriate tunnel buried depth, the settlement at the bottom of the reservoir increases with the increase of buried depth. When the depth of the tunnel is too shallow and the water level in the reservoir is high, the settlement of the reservoir bottom will significantly increase.



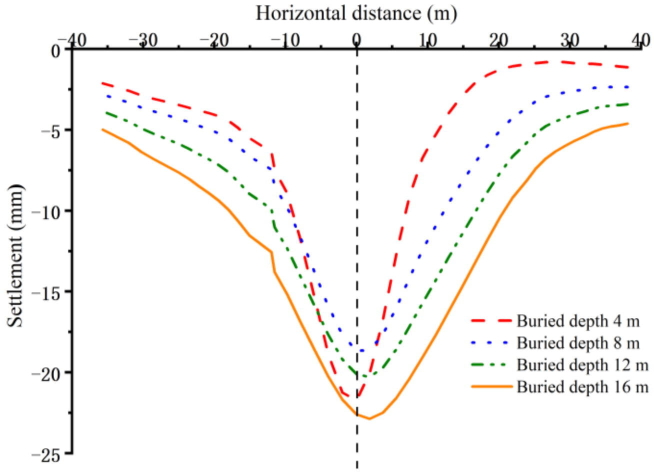
(a) Water depth 0 m



(b) Water depth 5 m



(c) Water depth 10 m



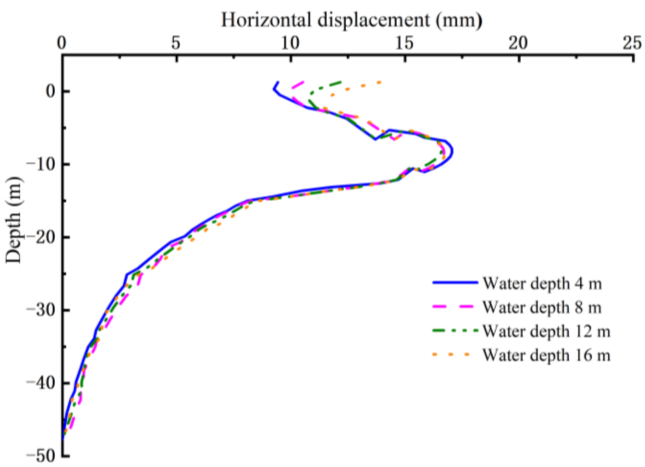
(d) Water depth 15 m

Fig. 5 Settlement of the reservoir bottom surface at each tunnel depth

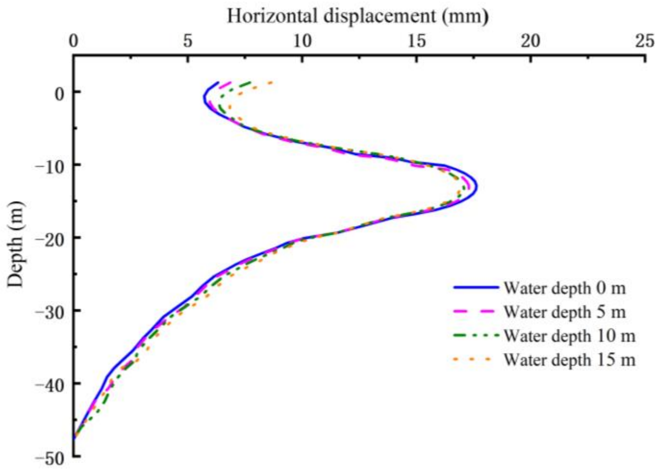
4.2 Horizontal displacement on the left side of tunnel

In order to investigate the horizontal displacement of the surrounding rock under various working conditions, a horizontal displacement map of the rock mass at different depths at line B on the left side of the tunnel is shown in Fig. 6.

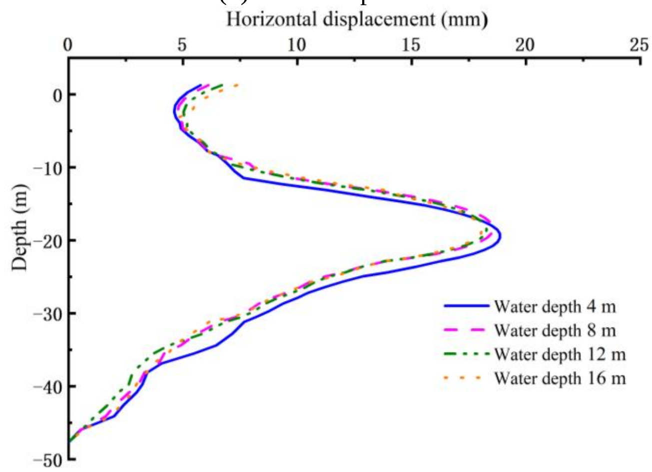
As shown in Fig. 6, when the tunnel is buried at a certain depth, the horizontal displacement curves of the surrounding rock at different depths on the left side of the tunnel basically overlap at different water levels. This indicates that the size of the upper reservoir water level has little impact on the horizontal displacement of the surrounding rock after excavation of tunnels with different buried depths.



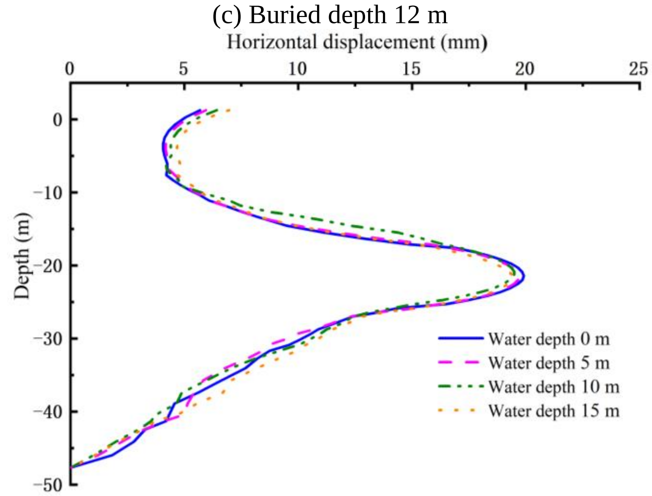
(a) Buried depth 4 m



(b) Buried depth 8 m



(c) Buried depth 12 m



(d) Buried depth 16 m

Fig. 6 Horizontal displacement on the left side of the tunnel

The horizontal displacement curves on the left side of the tunnel basically overlap at different water levels. Therefore, this paper selects a water level of 10 m to study the impact of tunnel excavation at different depths on the horizontal deformation of the surrounding rock. The horizontal displacement curve after non-linear fitting is shown in Fig. 7.

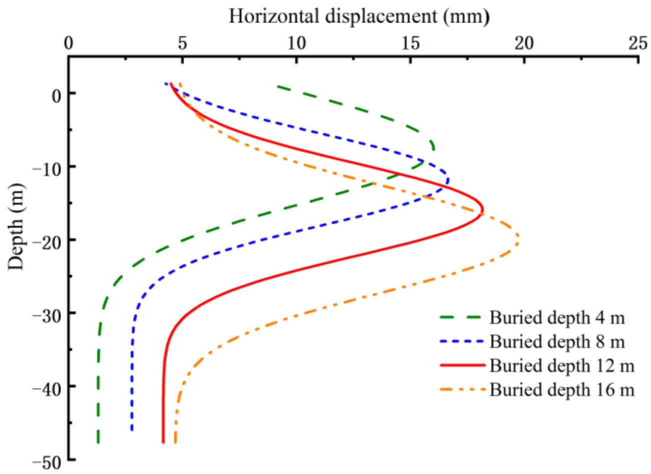


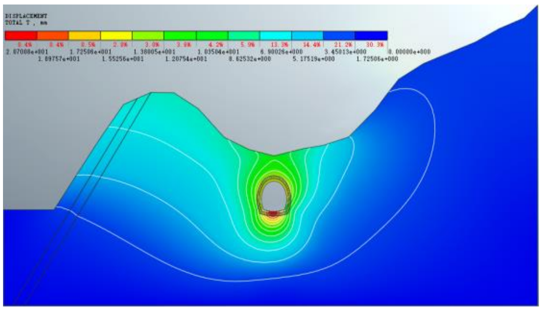
Fig. 7 Fitting curve of horizontal displacement on the left side of different buried depths

As shown in Fig. 7, for the surrounding rock at a smaller depth, the greater the buried depth of the tunnel, the smaller the maximum horizontal displacement. The deeper the tunnel is buried in the surrounding rock at a deeper depth, the greater the horizontal displacement value. The maximum horizontal displacement is positively correlated with the tunnel buried depth. The larger the tunnel buried depth, the greater the maximum horizontal displacement of the surrounding rock.

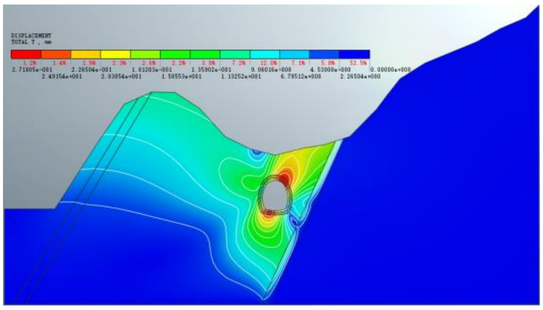
4.3 Analysis of Variational Rock Layer Parameters

In this engineering project, there are two layers of siltstone mutated rock strata in the surrounding rock near the tunnel, one of which is very close to the tunnel excavation location. In order to analyze the influence of the characteristics of mutated rock layers on the deformation of surrounding rock after tunnel excavation, this paper selects rock layers with different elastic modulus to analyze the deformation of surrounding rock. The model consists of five conditions: non mutated rock layers and mutated rock layers with elastic modulus of 7 MPa, 70 MPa, 700 MPa and 7000 MPa, respectively. The total deformation diagram of the surrounding rock is shown in Fig. 8.

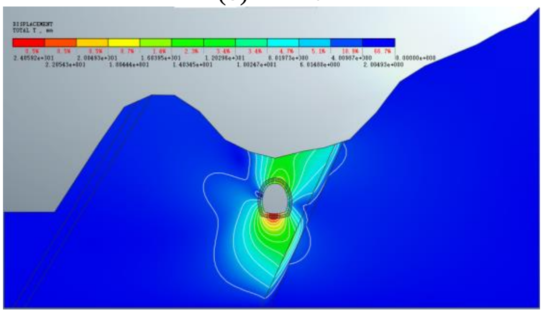
In the simulation, the elastic modulus of surrounding rock tuff is 1000 MPa and the thickness of mutated rock stratum is 2.2 m. As shown in Fig. 8(a) and (d), when there is no mutated rock layer or the elastic modulus of the mutated rock layer is close to the elastic modulus of the surrounding rock, the total deformation of the surrounding rock extends more uniformly from the tunnel to the surrounding area. When the elastic modulus of the mutated rock layer is small, as shown in Fig. 8(b) and (c), the mutated rock layer will prevent deformation from spreading to the other side of the rock layer. When the elastic modulus of the mutated rock layer is large, as shown in Fig. 8(e), the deformation equipotential line has a tendency to expand when passing through the mutated rock layer. That is, when the elastic modulus of the mutated rock layer is large, the range of surrounding rock affected by tunnel excavation will be expanded at the mutated rock layer.



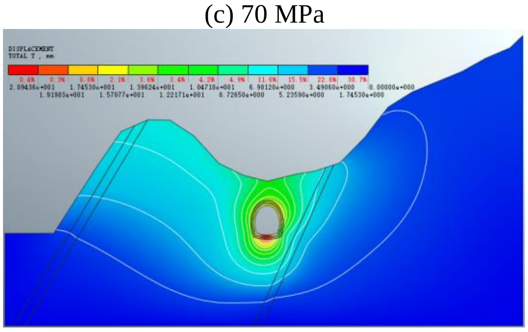
(a) non mutated rock layers



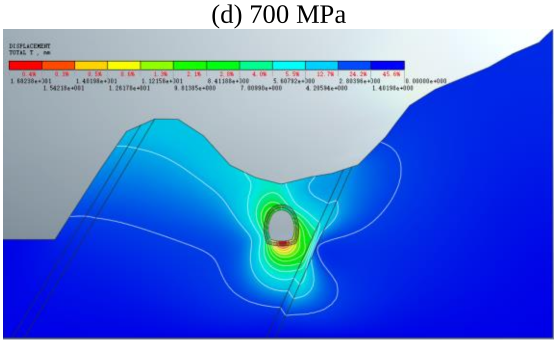
(b) 7 MPa



(c) 70 MPa



(d) 700 MPa

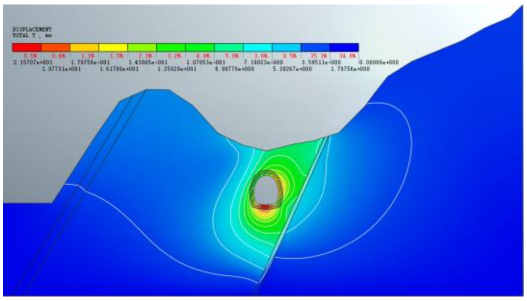


(e) 7000 MPa

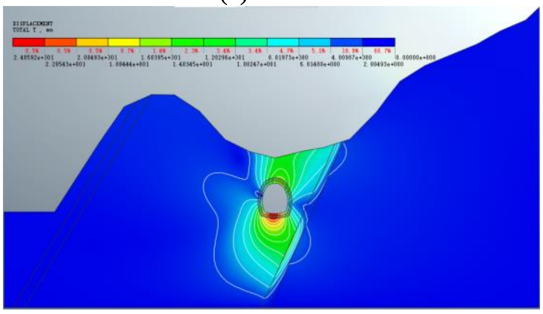
Fig. 8 Total deformation cloud map for surrounding rock

If the thickness *d* of the mutated rock layer is changed when the elastic modulus of the mutated rock layer is low, the total displacement cloud map of the surrounding rock is shown in Fig. 9. The elastic modulus of the mutated rock layer is 70 MPa.

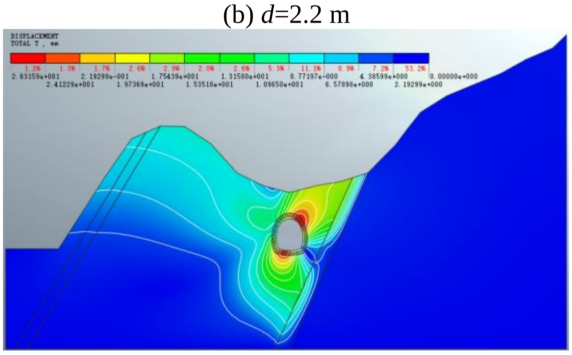
Comparing the cloud map of surrounding rock deformation caused by different thicknesses of mutated rock layers in Fig. 9, the blocked effect of mutated rock layers on deformation is also related to the thickness of the mutated rock layers. When the elastic modulus of the mutated rock layer is 70 MPa and the thickness of the mutated rock layer is 2.2 m, the deformation equipotential line enters the right side of the variable rock layer. When the thickness of the mutated rock layer is 1 m, the deformation on the right side of the mutated rock layer significantly increases. When the thickness of the mutated rock layer increases to 4 m, the equipotential line hardly passes through the mutated rock layer, and the deformation caused by the tunnel decreases significantly when passing through the mutated rock layer with smaller elastic modulus.



(a) *d*=1 m



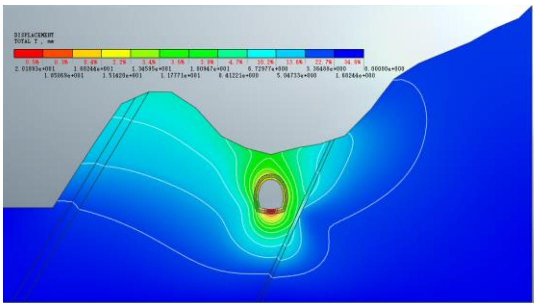
(b) *d*=2.2 m



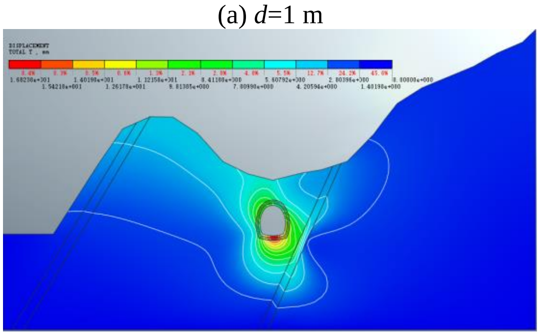
(c) *d*=4 m

Fig. 9 Total deformation for surrounding rock (Elastic modulus of mutated strata is 70 MPa)

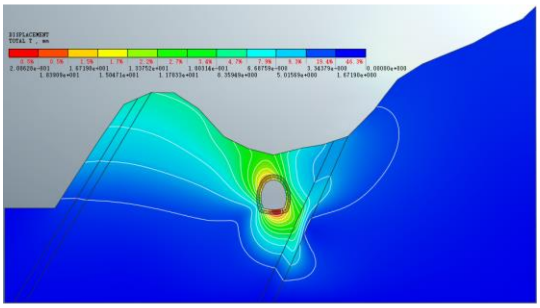
If the thickness *d* of the mutated rock layer is changed when the elastic modulus of the mutated rock layer is high, the total displacement cloud map of the surrounding rock is shown in Fig. 10. The elastic modulus of the mutated rock layer at this time is 7000 MPa.



(a) *d*=1 m



(b) *d*=2.2 m



(c) *d*=4 m

Fig. 10 Total deformation for surrounding rock (Elastic modulus of mutated strata is 7000 MPa)

Comparing the cloud map of surrounding rock deformation caused by different thickness mutated rock layers in Fig. 10, when the elastic modulus of the mutated rock layer is 7000 MPa, the deformation of surrounding rock caused by the tunnel tends to expand when passing through the mutated rock layer. The overall deformation of the surrounding rock is not significantly affected.

V. Conclusions

This paper relies on the Niuheling mountain tunnel project and uses finite element numerical simulation method to analyze the impact of a tunnel crossing a nearby reservoir in a mountainous area with mutated rock layers on the surrounding rock of the upper reservoir and tunnel. The main conclusions are as follows:

(1) Tunnel excavation will cause settlement of the bottom of the reservoir. When the tunnel depth is definite, the settlement of the reservoir bottom increases with the increase of the reservoir water level. However, the impact of water level on the settlement of the reservoir bottom will decrease with the increase of tunnel depth. The water level of the reservoir has no significant impact on the horizontal displacement caused by tunnel excavation. The maximum horizontal displacement increases with the increase of tunnel buried depth.

(2) When the water level of the reservoir through which the tunnel is excavated is shallow, the settlement of the reservoir bottom increases with the increase of the buried depth of the excavated tunnel. When the water level of the reservoir is deep, there is a significant increase in the settlement of the reservoir bottom caused by excavation of shallower buried tunnels.

(3) The properties of the mutated rock layers near the tunnel have a significant impact on the deformation of the surrounding rock. When the elastic modulus of the mutated rock layer is close to that of the surrounding rock, the total deformation of the surrounding rock extends more uniformly from the tunnel to the surrounding area. When the elastic modulus of the mutated rock layer is small, the mutated rock layer will prevent deformation from spreading to the other side of the rock layer. When the elastic modulus of the mutated rock layer is large, the deformation equipotential line tends to expand as it passes through the mutated rock layer.

(4) When the elastic modulus of the mutated rock layer is small, the expansion of deformation caused by tunnel excavation is related to the thickness of the mutated rock layer. If the elastic modulus of the mutated rock layer is small, the thicker the rock layer, and the greater the blocked effect of the mutated rock layer on the deformation of the surrounding rock. If the elastic modulus of the mutated rock layer is large, the overall impact of tunnel excavation on the deformation of the surrounding rock is not significant.

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