Numerical simulation analysis of tunnel construction mechanical response considering shotcrete hardening process

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Abstract. At present, tunnel construction mechanics studies basically do not consider the hardening process of shotcrete. In order to reveal the hardening process of sprayed concrete in a sulfate environment and the influence of sulfate corrosion on tunnel stability, the model parameters were determined in combination with the change rules of mechanical parameters of shotcrete obtained in the author's experiment. The MIDAS GTSNX finite element software was used to analyze the effect of the hardening process of the shotcrete, chemical corrosion, and physical corrosion of sulfate on the displacement and stress of the surrounding rock of the tunnel. The results show that considering the hardening process of shotcrete, the growth rate of tunnel clearance displacement in increases, and the stress increase slows in the early stage of shotcrete (the tunnel lining structure is applied, and the second step of excavation is carried out). With the increase of time or the construction steps, the stress of shotcrete increases significantly, and the clearance displacement growth rate significantly decreased. The influence of the chemical and physical corrosion of shotcrete on the stress and displacement of the surrounding rock of the tunnel is similar to considering the hardening process of shotcrete, indicating that sulfate corrosion has an inhibitory effect on the hardening process of shotcrete and increased construction risk.

1. Introduction

Generally speaking, the mechanical response of tunnel construction mainly refers to the stability analysis of the tunnel construction process, which is reflected in the stability analysis of tunnel surrounding rock to a large extent. According to the different assumptions of the surrounding rock constitutive model, it also has different modes to transfer force to support structures. Therefore, the research in this aspect mainly focuses on the stress calculation of surrounding rock. It mainly includes theoretical analysis, model test, numerical simulation and other aspects, and there are many related types of research [1-15]. However, the initial support, especially the hardening process of shotcrete, is often neglected, resulting in analysis deviation. Combined with the characteristics of the initial lining support of the tunnel, the stability analysis of the tunnel needs to reflect the four stages after the tunnel excavation: ① Unconstrained free deformation of the surrounding rock; ② Due to the application of the initial support, with the initial support hardening, the deformation speed of the surrounding rock continues to slow down; ③ The support structure is closed into a ring, the support pressure is the same as the surrounding rock pressure, both of which are deformed together; ④ The deformation tends to converge to achieve a stable state. Oreste [16] thinks that the hardening process of shotcrete has a significant influence on the displacement of the stratum and the support pressure. Therefore, applying the mechanical law of the hardening process of shotcrete obtained through the experimental study to the
mechanical analysis of tunnel construction will supplement the existing theory and method of tunnel stability analysis and make the tunnel stability analysis more close to the engineering practice. At the same time, in consideration of sulfate ion can react with the components of the concrete to produce chemical corrosion [20] and has a certain impact on the hardening of shotcrete. In this paper, the corrosive chemical effect of sulfate on concrete is collectively referred to as the chemical corrosion of concrete. When the sulfate solution is supersaturated in the concrete, it will produce sulfate crystallization in the concrete. Crystallization will affect the physical properties of concrete. The sulfate crystallization failure of concrete [21] is a typical physical erosion type. In this paper, the crystallization failure is called the physical corrosion of concrete.

2. Establishment of numerical model
Midas / GTS provides various mechanical models, which are widely used in underground engineering, including Drucker Prager model and Mohr-Coulomb model [1]. Drucker Prager model considers that material yield is a function of stress, which is widely used in limit analysis and low friction angle soft clay analysis. Mohr-Coulomb model considers that the material fails in shear yield, which is often used to analyze loose or cemented granular materials such as soil, rock, and concrete. In the previous experimental study, the gradient formula of the early hardening model of shotcrete is based on the gradient formula of concrete hardening [17]. In other words, based on the elastic model, the parameters of the elastic model - elastic modulus and uniaxial compressive strength are expressed to get the hardening formula of shotcrete. Therefore, the numerical analysis of early hardening of shotcrete is mainly based on the elastic model combined with the test, and it’s analysis results. In the numerical analysis, the Mohr-Coulomb model will be used to simulate the shotcrete of the tunnel. The Mohr-Coulomb model, which is often used in underground engineering simulation, is also used for the surrounding rock of the tunnel [19].

2.1. Model scope and boundary conditions
Considering the hardening process of shotcrete, it mainly reflects the changes of the initial support strength with time and then compares the corresponding changes of the stress and displacement of the tunnel caused by the changes of the initial support. Therefore, to reflect the time effect of tunnel excavation, the longitudinal variation process of the model should be considered. Theoretical analysis shows that the influence of tunnel construction on rock mass disturbance around the tunnel only occurs in a certain range and gradually decreases with the increase of the distance from the tunnel [5]. When the disturbance effect decreases to a certain extent, it can be ignored in engineering. Zienkiewicz and others proposed simplifying the semi-infinite plane strain model by using the truncated boundary method far enough away. Practice and theoretical analysis show that the surrounding rock disturbance caused by tunnel excavation is generally within the range of 3B from the center of the tunnel (B is the span of the tunnel), and the influence of tunnel excavation beyond this range is attenuated to 1 / 27 of the excavation site [8]. In a comprehensive consideration, the distance from the lateral boundary of the analysis model to the lateral contour of the tunnel is taken as 5B, the distance from the bottom boundary of the analysis model to the bottom of the tunnel is also taken as 5B, and the upper boundary is taken as the surface. Here, the two-lane highway tunnel is taken as the research object. The tunnel section is taken as five center circles with an inverted arch, the span is taken as 11.74 m, and the height is taken as 8.4 m. Therefore, the distance between the left boundary and the right boundary of the calculation model is taken as 117.4 m, the distance between the bottom boundary of the model and the bottom of the tunnel is taken as 58.7 m, and the buried depth of the tunnel is taken as 40 m, which belongs to the deeply buried tunnel, as shown in Figure 1.
2.2. Construction process control

The hardening formula of shotcrete involves time parameters [17]. In Midas, the elastic model cannot directly introduce time parameters. Therefore, two characteristics are introduced, which are linearly related to time variation. One is the subjective characteristic, that is, the excavation step. In the project, the excavation step is linearly related to time. In order to reflect the hardening process of shotcrete, the excavation distance of each step is set to be 1.0 m. Assuming daily excavation footage of 3.0 m, it is equivalent to dividing the excavation into three time periods to reflect the shotcrete changes in each period. However, the time change set by the subject cannot reflect the stress change of the model, so we need to introduce an objective characteristic, that is, the geo-stress release rate. In the first step of excavation, part of the geo-stress is released instantaneously, and the geo-stress is released continuously with time. By setting the release rate of the geo-stress increasing with the extension of the excavation step, the characteristics of the stress changing with time are reflected. Referring to the previous research results, for class V surrounding rock, the geo-stress release rate during construction is 25% ~ 45% [18], so the instantaneous geo-stress release during tunnel excavation is set as 25%, and with the completion of the hardening process of shotcrete for the initial lining, the geo-stress release rate gradually reaches 45%.

According to the experimental study on sulfate internal corrosion of early shotcrete [17], the numerical simulation working conditions (each state of shotcrete is a working condition) are divided into three groups: non-hardening group, hardening group, hardening sulfate chemical corrosion group, and sulfate physical corrosion group of shotcrete. The non-hardening group modeling method of shotcrete is common. The other three groups involve the change of grid properties, which will be slightly explained here. The normally established mesh of the initial lining of shotcrete is shown in Figure 2.

![Figure 1. Aerial view of the model and corresponding size data for each part.](image1)

![Figure 2. Shotcrete lining grid.](image2)
Figure 3. The initial lining of shotcrete grid and properties through boundary change.

When building a grid, the grid must be assigned a value. However, for the working conditions involving the hardening of shotcrete and sulfate corrosion, the value of the shotcrete grid needs to be changed. In the finite element simulation, only the time function constitutive relation, such as creep constitutive relation, can be directly introduced into the time parameter. The grid property can be changed and re-assigned by changing the time. The research focuses on the construction process, indirectly reflecting the time change through the construction steps and stress release. Therefore, by exerting boundary on the initial lining grid and assigning value to the boundary, the property of this part of the grid can be changed. The upper part of the model is a free boundary, and other boundaries are set as fixed boundaries. The modified effect model is shown in Figure 3.

On this basis, the construction steps are set to achieve the purpose of studying the hardening of tunnel shotcrete with construction excavation. The specific construction process is as follows:
(1) The initial geo-stress field is generated.
(2) Tunnel excavation at 1m at a time is a construction step without support during excavation (the stress release coefficient is set as 0.25).
(3) The tunnel lining structure is applied, and the second step of excavation is carried out (the stress release coefficient of the first step is increased by 0.06, and the stress release coefficient of the second step remains 0.25).
(4) The second step tunnel lining structure was applied, and the third step was excavated. The supporting properties of the first step changed once (the stress release coefficient of the first step and the second step increased by 0.06, and the stress release coefficient of the third step was 0.25).
(5) The third step tunnel lining structure is applied, and the fourth step is excavation. The support properties of the first step change for the second time (the stress release coefficients of the first step, the second step, and the third step are increased by 0.06. Step stress release coefficient 0.25, so far, the fourth step construction is completed).
(6) Repeat the above process until the construction of the lining supported by the last step changes twice after the completion of the construction.

2.3. Model material parameters
During the construction, it is assumed that the surrounding rock parameters are unchanged, and the surrounding rock parameters are shown in Table 1. This paper mainly studies the change of displacement and stress of the tunnel caused by the change of initial lining parameters. The initial lining parameters are shown in Table 2.

| Table 1. Model parameters of Grade V rocky surrounding rock |
|-----------------------------------------------------------|
| Surrounding Rock Type | Unit Weight (kN/m³) | Deformation Modulus E (GPa) | Poisson Ratio | The angle of Internal Friction (°) | Cohesion c (MPa) |
|------------------------|---------------------|-----------------------------|--------------|-----------------------------------|-----------------|
| Grade V Rocky Surrounding Rock | 20 | 2.0 | 0.35 | 27 | 0.20 |
The variation of shotcrete parameters is selected according to the test [17], and condition 1 represents the conventional tunnel initial lining parameters. Conditions 2 to 4 correspond to the parameters obtained in the test during the hardening process of shotcrete and the parameters after internal corrosion by sulfate.

**Table 2.** Shotcrete parameters under different working conditions and different construction steps.

| Working Condition | Lining Type | Unit Weight (kN/m²) | Elasticity Modulus E (GPa) | Poisson Ratio | Compressive Strength (MPa) |
|-------------------|-------------|---------------------|---------------------------|--------------|--------------------------|
| ①                 | ①          | 22                  | 10.2                      | 0.25         | 35.7                     |
|                   | step1       | 24.1                | 2.7                       | 0.25         | 11.99                    |
| ②                 | ②          | 22.6                | 6.9                       | 0.25         | 27.51                    |
|                   | step 2      | 21.4                | 9.4                       | 0.25         | 34.52                    |
|                   | step 3      | 23.8                | 2.3                       | 0.25         | 7.67                     |
| ③                 | ③          | 21.2                | 5.8                       | 0.25         | 20.33                    |
|                   | step 2      | 23.1                | 7.5                       | 0.25         | 24.84                    |
|                   | step 3      | 21.8                | 3.1                       | 0.25         | 11.15                    |
| ④                 | ④          | 20.9                | 4.2                       | 0.25         | 12.71                    |

**Working condition:** ① non hardening group ② hardening group ③ hardening sulfate chemical corrosion group ④ hardening physical corrosion group ⑤ hardening initial lining with chemical corrosion ⑥ hardening initial lining with physical corrosion.

**Lining Type:** ① no hardening initial lining ② hardening initial lining ③ hardening initial lining with chemical corrosion ④ hardening initial lining with physical corrosion.

3. **Analysis of simulation results**

The mechanical response caused by the change of tunnel supporting structure is mainly reflected in the stress change of surrounding rock and the deformation of the tunnel. From the analysis of the main stress nephogram of various working conditions, it can be found that no matter whether the hardening process of shotcrete is considered or not, the main distribution characteristics of the stress in the deep tunnel will not be changed, features of pressure arch are still significant. Considering the hardening process of the initial lining of shotcrete, it has little influence on the stress distribution around the tunnel without involving the tunnel damage. Considering the hardening process, the rigidity of the support structure increases gradually. In the case of small stiffness in the early stage, it will only bear small surrounding rock pressure; that is, in the form of expression, the shotcrete support structure will deform under the small surrounding rock pressure. After the shotcrete is subjected to chemical corrosion, its rigidity is smaller than the hardening condition, and the surrounding rock pressure is smaller; the change characteristics under the physical corrosion condition are similar, the smaller support rigidity leads to the smaller support force.

Under each working condition, in the three steps of initial excavation, with each step of excavation, the geo-stress is released continuously [18]. The deformation of tunnel leads to the decrease of relative stratum pressure of surrounding rock and the formation of a stress funnel. In the case of no collapse of the tunnel, the phenomenon can be considered that the initial lining of the tunnel as flexible support plays a role in supporting the tunnel and achieves the purpose of releasing the geo-stress. Comparing the stress nephogram of each excavation step under four working conditions, it can be found that in the working condition without considering the hardening of shotcrete, the stress funnel phenomenon is formed only in the third step, which is because the initial lining of shotcrete always maintains high elastic rigidity, and only under the condition of large surrounding rock pressure, a certain stress release occurs. The value of the main stress of the tunnel vault is relatively large, and the main stress increases to about 10% with the release of about 7% geo-stress increment in each excavation step. Obviously, due to the large stiffness of the initial lining of shotcrete, the stress release caused by the tunnel excavation is more transmitted to the shotcrete lining, which has completed the support.

The working conditions of chemical corrosion and physical corrosion are very similar to those
considering the hardening process of shotcrete. Under the condition of physical corrosion, each step of geostress release is about 7%, and the value of main stress increases by less than 5%. Considering the conduction of stress release brought by the later excavation, the proportion of new stress borne by shotcrete lining is lower after each excavation. In practical engineering, no matter geotechnical engineering or structural engineering, the slow rise of the stress of supporting structure under the condition of bearing increasing load is the sign of relative large plastic deformation or even failure tendency of the structure. Once the load increases and the stress of the structure remain unchanged, it can be considered that the material has reached the plastic failure. The stress of tunnel vault under various working conditions is compared as shown in Figure 4:

![Stress variation diagram](image1)

**Figure 4.** Stress variation diagram under different working conditions considering the hardening process of shotcrete.

With the linear release of geostress, the stress of the tunnel initial lining without considering the hardening process increases rapidly. However, the stress of the lining considering the hardening process increases slowly at the beginning and accelerates with the hardening process. The hydration process of shotcrete under sulfate physical corrosion is greatly affected, which can not meet the requirements of concrete specifications. Therefore, the stress process shows the phenomenon of growth at first, but then growth stagnation.

Through the above analysis, it is believed that the change of geostress response caused by different characteristics of shotcrete lining and the change of geostress caused by the influence of sulfate corrosion on shotcrete lining can be clarified.

![Settlement diagram](image2)

**Figure 5.** Settlement of tunnel vault after excavation is completed.

The change of stress is usually corresponding to the change of displacement. The curve of the control point displacement of arch vault settlement and arch waist convergence with the change of tunnel
excavation and shotcrete characteristics is shown in Figure 5.

The disturbance of tunnel excavation and the continuous release of ground stress lead to the random distribution of settlements at each point of the longitudinal vault. However, it can also be seen that the decrease of the characteristics of the shotcrete lining causes the greater fluctuation of the settlement of the longitudinal points of the tunnel. Under the condition of physical corrosion, the settlement of the tunnel vault is the largest. The settlement value of the point at the tunnel entrance is the largest under four working conditions. Select this point to analyze the settlement change after each excavation of the tunnel (Figure 6).

![Excavation step of tunnel](image)

(a) The displacement change value of the maximum settlement point of the tunnel with the simulated construction step.

![Fig 6. Displacement change of the maximum point of tunnel arch settlement with excavation steps.](image)

(b) Displacement change value of the maximum settlement point of the tunnel after excavation in four steps after support.

**Figure 6.** Displacement change of the maximum point of tunnel arch settlement with excavation steps.

In Figure 6a, the third step is to start lining support (the first step is to balance the initial geostress and clear the displacement, and the second step is to excavate the tunnel). Figure 6a shows that even under the physical corrosion condition with the most serious damage to the shotcrete characteristics, the
settlement of the tunnel vault begins to converge after the excavation to the sixth step. The main difference between the four working conditions is in the three steps after shotcrete lining support. In these construction steps, the change of lining characteristics and the release of geostress are rebalanced by displacement. Figure 6b compares the four-step displacement of each working condition after support construction. It is obvious that the linear release of geostress with excavation step directly corresponds to the linear increase of vault settlement in this working condition because the hardening process of shotcrete is not considered. In considering the hardening process of shotcrete, the first two steps of support produce a large settlement of the tunnel vault. However, after the third step, the increase of settlement is significantly reduced. Combined with the conclusion of stress analysis, in the first two steps of settlement, the stress redistribution reached a new balance; after that, even if the stiffness of the shotcrete support structure increases, it will not bear more load. The physical corrosion and chemical corrosion working conditions are significantly larger than those without corrosion factors in settlement or settlement increment of each step.

Figure 7 shows the change curve of convergence displacement with longitudinal distance at each point of arch waist after tunnel excavation under four working conditions.

Similar to the settlement of the tunnel vault, the excavation disturbance and continuous release of geostress results in the convergence of each arch waist point along the longitudinal direction of the tunnel showing a random distribution state. Under the condition of physical corrosion, the convergence value of the tunnel arch waist is the largest. It is still the maximum convergence point at the tunnel entrance.
(b) Displacement change value of convergence point of tunnel entrance arch waist with four steps excavation after support.

Figure 8. Change of convergent displacement of tunnel entrance arch waist with excavation steps.

Figure 8 shows the convergence displacement change of the two sides of the arch waist at the tunnel entrance under four working conditions.

It can be seen from Figure 8a that the convergence of tunnel arch waist also tends to convergence after the seventh step of the simulation. The significant difference under different working conditions is that the convergence displacement value is still reflected in the first few excavation steps after shotcrete support. It can be seen from Figure 8b that in the working condition, without considering the hardening process of shotcrete, the increase of convergence displacement of arch waist increases linearly with the increase of excavation step (the increase of geostress release). In considering the hardening process of shotcrete, the displacement of the arch waist of the tunnel after the first two steps is large after supporting. After the third step, the increment of displacement is rapidly reduced. The convergence amount and each step convergence increase, the physical corrosion condition and chemical corrosion condition are significantly larger than those without corrosion factors. In chemical corrosion and physical corrosion, there is still a large deformation increment in the three-step excavation time (It is generally considered that the shotcrete has reached the hardening standard) after the support construction. The shotcrete lining damaged by sulfate corrosion can't bear the larger geostress, so it can only redistribute the stress through deformation. In this process, large deformation may bring two risks. First, the initial lining of shotcrete belongs to the flexible support, but the deformation also has a limit value. Too large deformation may lead to the direct damage of the support; second, because the deformation is too large, it affects the normal use function of the tunnel.

Generally speaking, in the process of tunnel construction, the damage of sulfate corrosion to the initial lining of shotcrete results in the increase of displacement value and manifest as the process of slow convergence. The existence of sulfate corrosion not only damages the final mechanical properties of the hydration reaction of shotcrete but also affects the hydration reaction process of shotcrete itself. In tunnel construction, after the normal initial lining of shotcrete construction, the hardening time of 24 hours can generally ensure the continued excavation. However, due to the influence of sulfate corrosion, the shotcrete cannot be normally hardened, which leads to cracking and damage of the initial support.

4. Conclusion

MIDAS GTS NX finite element software was used to simulate the time effect of the variation of shotcrete characteristics by setting the geostress conditions and construction steps in combination with the mechanical parameter variation law of shotcrete materials obtained in the experiment.

In the process of tunnel construction, considering the hardening process of shotcrete is more in line
with the engineering practice, in the latter two construction steps after the shotcrete construction of the initial support of the tunnel, the vault settlement and the convergence displacement of the arch waist increasing, and the increase of the stress slows down. With the increase of time (construction step), the characteristic improvement brought by the hardening of shotcrete shows that the stress of shotcrete increases obviously, and the settlement of arch vault and the convergence displacement of arch waist decrease significantly.

The influence of sulfate chemical corrosion and physical corrosion on the hydration process of shotcrete material properties is shown in the early stage (1-2 steps of construction) after shotcrete construction. The calculation results of surrounding rock stress and tunnel displacement are similar to those under the condition of considering shotcrete hardening. However, the difference in measurement values is obvious. However, in the later period, the hardening characteristics of shotcrete caused by sulfate chemical corrosion and physical corrosion can not be effectively improved, which leads to the small stress change of shotcrete (small stress value) and the increasing settlement of tunnel vault and convergence displacement of the arch waist, which brings great risk to construction safety.

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