Study on the Aging Deterioration Curve of Tunnel Lining in Water Rich Area

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Abstract. In this paper, the main influencing factors of tunnel lining deterioration are summarized, and the stability of surrounding rock, structural safety and the law of annual change of crack width under combined deterioration factors are analysed by numerical analysis method. The results show that the change of groundwater level has the most significant influence on the stability of surrounding rock. The rise of groundwater level makes tunnel appear obvious phenomenon of vault sinking and invert floating. When the water level has passed the vault, the lining structure has a significant reduction of safety factor and an increase of crack width. The deteriorated surrounding rock is prone to damage under the influence of groundwater, which directly shows an obvious expansion of plastic zone. The deterioration of lining material will not have a significant impact on the stability of surrounding rock and the structural safety factor. Among various deterioration factors, the position of wall feet on both sides and the invert are the most disadvantageous position in the tunnel. They are under high risk of cracks and seepage, which should be paid attention during the tunnel construction, operation and maintenance.

1. Introduction
The deterioration of tunnel structure caused by groundwater is mainly manifested in three aspects. First, the rise and fall of groundwater level will change the external water pressure of tunnel lining. Second, the water rock interaction will cause a deterioration of surrounding rock. Third, the groundwater will cause a deterioration of reinforced concrete materials. Under the effect of groundwater pressure, the lining structures may appear deformation, cracking and even local damage, which may threaten the safety of the tunnel.

The degradation of surrounding rock is a complex process [1]. Surrounding rock will deteriorate obviously under the condition of water [2], especially when it saturates under groundwater for a long time, or when the head pressure changes periodically due to the change of water level[3][4]. It should be noted that the effect of groundwater on the deterioration of reinforced concrete structure is not simply the effect of carbonization, ion erosion or water pressure, but the result of complex multi factors. Some studies have shown that the existence of external water pressure will affect the transport mode of erosion materials to a certain extent [5][6][7]. Taking chloridion as an example, the lining
structure side which contacted with surrounding rock can be considered as saturated. At this time, the transport mode of chloridion in concrete is mainly diffusion. However, when the external water pressure is large enough, the transport mode of chloridion will change to infiltration.

In this paper, by means of numerical simulation, the stress characteristics, deformation law, failure state and the variation of structural safety of lining under the condition of groundwater level change, surrounding rock deterioration, lining material deterioration and their combinations are studied. It can provide basic technical support for the safe operation and maintenance of existing tunnels.

2. Numerical Model and Parameter Selection

2.1. Numerical Model and Boundary Condition

The tunnel is located in class V surrounding rock with a buried depth of 60m. The horizontal displacements of the front, rear, left and right boundaries are zero, and the vertical displacement of the bottom boundary is zero. The dimension of the numerical model is 120m×100m×50m. The middle position of the numerical model along longitudinal direction is used for analyzing, i.e. the position of 25-26m. The numerical model and finite element mesh are shown in Figure 1. The secondary lining uses a 50cm thick C35 reinforced concrete. The mechanical parameters of surrounding rock and tunnel lining are shown in Table 1.

| Parameter                  | $E$ (GPa) | $\nu$   | $\gamma$ (kN·m$^{-3}$) | $\phi$ (°) | $c$ (MPa) |
|----------------------------|----------|---------|-------------------------|----------|----------|
| Class V surrounding rock   | 2        | 0.35    | 20                      | 27       | 0.2      |
| C35 concrete               | 32.5     | 0.2     | 23                      | —        | —        |
| HRB400 reinforcement       | 200      | —       | —                       | —        | —        |

2.2. Selection of Deterioration Parameters for Numerical Simulation

2.2.1. Variation of Groundwater Level.

During the numerical simulation, it is assumed that the groundwater level in the initial state is just below the invert, and the groundwater level rises by 2.5m every five years. By simulating the increase of hydrostatic pressure on the external surface of secondary lining caused by the gradual rise of water level in 100 years, the changing law of lining safety and crack width are obtained.

2.2.2. Aging Deterioration of Surrounding Rock.

Take the surrounding rock of class V in this numerical model as an example. The deformation modulus E varies from 1 to 2GPa. In the numerical analysis, the change of surrounding rock parameters is simplified. Assuming that the deformation modulus decreases by 0.05GPa every 5 years, then the corresponding mechanical parameters can be obtained.
2.2.3. Aging Deterioration of Lining Materials.

For C35 concrete with an elastic modulus of 32.5GPa, the aging change model of the elastic modulus is shown in Figure 2.

3. Analysis of Numerical Simulation Results

3.1. Displacement Analysis

By comparing the vertical displacement nephogram (as shown in Table 2) of three different deterioration factors after 0-year and 100-year deterioration, it can be seen that:

1. When the groundwater level rises and the surrounding rock deteriorates over years, it can be seen that the vertical displacement of surrounding rock changes significantly. The displacement of the surrounding rock under invert is 1.2cm when it not deteriorate, and 3.11cm when it deteriorates for 100 years., which leads to an obvious invert floating, and the vertical displacement of surrounding rock at the vault is also gradually increasing.

2. With the rise of groundwater level and the deterioration of lining materials, the upward displacement of the surrounding rock at invert and the downward displacement of the surrounding rock at vault are increased, and the upward displacement of invert is bigger.

3. When the groundwater level rises, and both the surrounding rock and lining materials deteriorate, it can be observed from the table that the displacement of surrounding rock at the invert increases from 1.2cm to 3.4cm. In contrast, the vertical displacement of surrounding rock at the vault increases by only 0.33cm.

Table 2. Vertical displacement of surrounding rock under combined deterioration factors(m)

| Deterioration Factors                              | Time(years) |
|---------------------------------------------------|-------------|
|                                                   | 0           | 100          |
| Water level change and surrounding rock deteriorate| ![Image](image1.png) | ![Image](image2.png) |
Water level change and lining materials deteriorate

Water level change, surrounding rock, and lining materials deteriorate

3.2. Plastic Zone Analysis
From the table of plastic zone under combined deterioration factors (Table 3):

| Deterioration Factors                                      | Time (years) |
|-----------------------------------------------------------|--------------|
|                                                            | 0            | 100          |
|                                                            | FLAC3D 5.01  | FLAC3D 5.01  |
| Water level change and surrounding rock deteriorate       |              |              |
|                                                            |              |              |
| Water level change and lining materials deteriorate       |              |              |
|                                                            |              |              |
| Water level change, surrounding rock, and lining materials deteriorate |              |              |

(1) When there is no deterioration, the plastic zone of surrounding rock is mainly distributed at the both sides of arch rings, height is about 18m and the width is about 6m. The damage state of surrounding rock elements is mainly shear failure.
(2) When the groundwater level rises and the surrounding rock deteriorates for 100 years, the plastic zone of surrounding rock is obviously enlarged, and the number of elements damaged by tension around the tunnel is significantly increased.

(3) When the groundwater level rises and the reinforced concrete lining material deteriorates, the plastic zone of surrounding rock tends to expand gradually. Obvious shear failure occurred in the surrounding rock elements at springer, followed by the surrounding rock at the shoulders.

(4) When the groundwater level rises and the surrounding rock and reinforced concrete materials deteriorate, it can be seen that the plastic zone of surrounding rock is basically the same as that of water and surrounding rock deteriorate. It shows that the rise of groundwater level and the deterioration of surrounding rock have a great impact on the surrounding rock around the tunnel, which makes the surrounding rock easy to be damaged and thus poses a threat to the safe operation of tunnel.

3.3. Influence of Combined Deterioration Factors on Lining Safety

The change laws of structural safety factor under combined deterioration factors is shown in Figure 3

As shown Figure 3:

(1) With the increase of deterioration time, the overall safety of lining structure is in a decreasing trend. The safety factor of feet is at the lowest position from the beginning of deterioration, with the deterioration, the safety factor of invert decreases rapidly, which is lower than that at the feet in a few decades. The safety of tunnel feet and invert, which has been in the deterioration environment for a long time.

(2) With the rise of groundwater level and the deterioration of surrounding rock, the overall safety of lining structure is becoming worse. However, when the groundwater level increases year by year along the arch ring, that is, when the groundwater level increases for about 0-25 years, the safety factor of each position of the tunnel gradually and slowly decreases. When the groundwater level
passes the vault, the decreasing speed of safety factor begins to accelerate, and that of invert is greater than any other portions.

(3) When the groundwater level rises and the surrounding rock and lining materials deteriorate at the same time, the safety of tunnel is improved obviously in the early stage of deterioration. By reducing the elastic modulus to simulate the deterioration of reinforced concrete material will increase the deformation capacity of lining and reduce the concentrated stress of tunnel under the same conditions. However, with the increase of deterioration time, the safety factor decreases rapidly and reaches the same value as the deterioration of surrounding rock and groundwater.

4. Conclusion
(1) When the groundwater exists, the deteriorated surrounding rock is much easier to be damaged, which leads to the significant expansion of plastic zone. The feet of tunnel and invert are always the positions with low safety factor and continuous increase of crack width. Especially in the case of deterioration to about 50 years, the safety factor decreases rapidly and the crack width increases significantly.

(2) When lining materials deteriorate over the years and underground water level rising, tunnel invert floats a little. The plastic zone is mainly at tunnel feet. Due to the reduction of elastic modulus, the deformation ability of lining is enhanced, which makes tunnel safety slightly increased.

(3) When the groundwater level rises and surrounding rock and lining materials deteriorate at the same time, the vertical displacement of surrounding rock reaches the maximum value, and the plastic zone reaches the maximum range. The internal force of lining structure is slightly reduced, and the safety factor at the early stage of deterioration is significantly increased. The change law of crack width is basically the same when the reinforcement ratio is 0.5% and 0.25%. The value of crack width is similar to that of surrounding rock and groundwater deterioration, but larger than that of lining material and groundwater deterioration.

(4) The variation of groundwater level has the most significant influence on the stress characteristics of tunnel lining and the stability of surrounding rock. Tunnel feet and invert are the high incidence position of cracks and water leakage in tunnels, which need to be paid attention to.

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References
[1] Jiang, Q., Feng, X.T., Cheng, G.Q. (2008) Study on constitutive model of hard rock considering surrounding rock deterioration under high geostresses. J. Chinese Journal of Rock Mechanics and Engineering, 27(1): 144-152.
[2] Huang, M., Liu, X.R., Deng, T. (2012) Study on the creep properties of T2b2 siltite in terms of the damage law induced by water. J. Journal of Fuzhou University (Natural Science Edition), 3: 399-405.
[3] OJO, O., BROOK, N. The effect of moisture on some mechanical properties of rock. J. Mining Science & Technology, 10(2): 145-156.
[4] Liu, X.R., Jiang, D.Y., Yu, H.L. (2000) Study of the effect of water to rock mechanics characteristics. J. Industrial Minerals & Processing, 29(5): 17-20.
[5] Zhao, Y.D., Zhao, T.J., Wan, X.M., et al. (2011) Environmental corrosion mechanism of underground concrete structure in coastal area. J. China Concrete, 5: 68-72.
[6] Kong, Chao, Gao, Xinqiang, Cao, Li, & Liu, Kai. Analysis of the failure of primary support of a deep-buried railway tunnel in silty clay. Engineering Failure Analysis, 66, 259-273.
[7] GAO Xinqiang, QIU Wenge, & KONG Chao. (2013). Test study on the variation law of seepage field during the construction process of high water pressure tunnel. China Railway Science, 34(1), 50-58.