Stress based safety evaluation of tunnel liners situated in swelling rock masses

Yuting Zhang, Shuling Huang and Xiuli Ding

Changjiang River Scientific Research Institute, Wuhan, China

zhangyuting@mail.crsri.cn  https://orcid.org/0000-0003-0926-9148

Abstract. The liners of tunnels excavated in swelling rocks are vulnerable to the expansive behaviour of surrounding rock masses. To look into this issue, this paper performs a study on a tunnel situated in silty mudstone rock mass with sufficiently humid condition. The swelling behaviour of this strata is investigated based on indoor laboratory tests using samples drilled from field representative rock mass layer. The mineral content test shows there are considerable clay, which contribute to the exhibition of medium expansibility of rock mass. To estimate the stresses in tunnel liners and optimize the design schemes, numerical calculations are done to consider various loads, including swelling pressure, excavation load and ground water pressure. The results show that the differences of tunnel profile and liner thickness yield remarkable variations of stresses in liners. By summarizing the results, an optimized tunnel liner design scheme is proposed. The work of this paper gives a general guideline for safety evaluation of tunnel liners situated in swelling rock masses.

1. Introduction

It remains a continuous challenging issue for the rock mechanics profession to handle the construction of tunnel excavated in adverse geological conditions, such as squeezing, swelling, and faulted grounds. Because a series of geological hazards, including large deformation, rock rupture, and roof collapse are always present during the excavation process. Many scholars [1-2] have looked into this issue with special attentions on soft rock masses and the generation of large deformation of surrounding rock masses. Other scholars [3-5] focused on faulted grounds and established the connection between this typical ground condition and roof collapse, which accounts for the primary failure cases in tunnels. Einstein [6] studied the swelling rocks and found they can lead to large deformation of surrounding rock masses (Figure 1) and bring about rock support failure(Figure 2) and fracture tunnel liners (Figure 3). Besides the ground conditions that cause threat to tunnel liners, the ground water pressure acting on the external surface of liners is another concern for designers. It is common knowledge that the design concerns should be addressed carefully using sophisticated techniques to achieve a satisfactory answer and a reliable solution. To cope with this issue, the proposed paper gives a case study on a water conservancy tunnel excavated in humid silty mudstone layer. Multiple researches are performed to study the mechanical properties of surrounding rock masses and the ground water effect. Based on the proposed design schemes, numerical calculations are done to consider the impacts of swelling rocks and ground water. The stresses in tunnel liners are evaluated to optimize the design profile of tunnel.
2. Rock sample tests

2.1. Overview
The focused tunnel is a water conveyance tunnel in China. The tunnel is about 40 km long and over 2000 m in depth. Its profile nears a circle shape with a diameter of 5 m. The studied tunnel part is found in silty mudstone strata with very poor rock mass qualification. Based on the results of geological exploration, the rock mass on the tunnel surfaces are constantly wet and poorly cemented (Figure 4). Due to the adverse geological conditions of observed rock masses, a big safety concern rises as the potential geological hazards are highly possible.

2.2. Tests of rock swelling capability

2.1.1. Apparatuses. Figure 5 shows the apparatuses adopted for measurement of rock expansibility. The axial and radial expansion ratio under free expansion condition, the axial expansion ratio under later restraint conditions are obtained as the primary indexes that describe the swelling behaviour.

2.1.2. Sample preparation. The samples consist of two types. The cubic samples (Figure 6) are about 60 mm long. The cylindrical samples (Figure 7) are 40 mm to 50 mm in diameter with a height of 20 mm. Their two end faces are parallel to each other. For each kind of test three rock samples are prepared.
2.1.3. Results. The free expansion test shows that the rock samples have significant time effect on expansibility. The samples are fully disinterated at the end of test (Figure 8). The rocks are completely loosened due to argillization effect. Figure 9 and Figure 10 plot the axial expansion ratio and radial expansion ratio, respectively. It is observed that the expansion ratio increases rapidly for the first hour of water immersion. At the seventh to eighth hour, the expansion ratio slows down and gradually becomes stable. It is measured that the axial expansion ratios are 6.25%, 6.38%, and 4.07% for the three rock samples. The radial expansion ratios are 1.66%, 1.30%, and 3.23%. In comparison, the axial expansion ratios are much larger than the values in radial direction. Figure 11 gives the variation of axial expansion ratio considering lateral restraint condition. It is found that the samples begin to expand remarkably about two hours after the water immersion. The expansion speed becomes stable about 24 hours after the water immersion and the expansion ratios maintains stable at the values of 6.60%, 8.56%, and 6.81%, respectively. In comparison, the expansion velocity during the initial two hours after water immersion for samples without lateral restraint is considerably larger than the samples considering lateral restraint. However, the maximum expansion ratio is recorded by rock samples with lateral constraint and it also takes longer time for these samples to achieve a convergent expansion ratio. Figure 12 gives the variation of swelling pressure subjected to water immersion. It is shown that the swelling pressure increases very quick and achieves 92 kPa, 411 kPa, and 140 kPa at the eighth hour of water immersion. Approximately about 24 hours later, the swelling pressure gradually becomes stable and the values are 402 kPa, 550 kPa, and 434 kPa.
2.1.4. **Summary.** It is easily concluded from the above data that the rock samples exhibit typical feature of swelling rocks. The plotted curves all show significant time effect, which may be a probable explanation that the surrounding rock deformation of tunnels require a longer duration to achieve convergence compared to conventional hard rock masses. Besides, the obtained swelling pressure data show that the swelling rocks will produce additional load subjected to water immersion. This point is particularly important for tunnel designers because corresponding countermeasures are necessary to resist the newly generated load.

2.3. **Mineral analysis**

Based on the mineral composition analysis results, the montmorillonite, illite, quartz, sodium feldspar, and potassium feldspar account for 30%, 10%, 45%, 10%, and 5%, respectively. As the montmorillonite and illite are hydrophilic minerals, it is obvious that their existence makes the rocks expansive.

2.4. **Groundwater conditions**

Based on drilling exploration, the rock mass permeability at the silty mudstone tunnel section is slight to minor degree. It is forecasted that the excavation surfaces will be wet during tunnel construction, but the possibility of water inrush is small. Despite the influence of groundwater on tunnel stability is minor, its potential effect on lining structures during the operation period cannot be neglected. As the excavation surfaces will be fully covered by lining structures, the groundwater level can be restored to its original state prior to tunnel construction. Thus, the static water load acting on the external surfaces of lining structures will be a major effect determining their stress magnitude and distribution. Therefore, to fully consider the impact of groundwater on tunnel lining structure during operation period, the groundwater pressure acting on the lining structures is assumed based on drilling hole data and field observation of traffic auxiliary tunnel.

3. **Numerical calculation**

3.1. **Design schemes**

Four different design profiles are proposed to compare their adaptability to the encountered rock mass condition. Type A, B, and C have similar profile shape but are different in lining thickness. Type D is an almost circular profile with a relatively small lining thickness.
Figure 13. Four design profiles of the water conveyance tunnel

3.2. Various load conditions
For each design profile of the tunnel, various load combinations are considered. They are listed in Table 1 and detailed as below. It should be noted that, besides the mentioned loads in Table 1, the deadweight of concrete lining is also considered.

| No. of working conditions | Excavation load | Groundwater effect | Swelling pressure | Grouting pressure |
|----------------------------|-----------------|--------------------|------------------|------------------|
| 1                          |                 | √                  |                  |                  |
| 2                          | √               | √                  |                  | √                |
| 3                          | √               | √                  | √                | √                |

3.2.1. Excavation load. It refers to excavation release load of surrounding rock during tunnel construction period. A proportion of 5% excavation release load is considered to include the additional load of rock masses acting on lining structures due to the time-dependent characteristics of swelling rocks.

3.2.2. Grouting pressure. The lining structures are usually poured in field. As concrete volume will become smaller within setting-time, the upper part of lining structure may not be in good and solid contact with surrounding rocks. Therefore, the backfill grouting is always performed towards the upper 120 degree of the tunnel section to fill the probable gaps. Based on design recommendations, a grouting pressure of 0.1 MPa is considered and applied to the external surface of lining structures.

3.2.3. Ground water pressure. Generally, an external water pressure reduction coefficient, which ranges from 0 to 1.0, will be considered to describe the influences of groundwater pressure. This value is multiplied by the height difference between the tunnel roof elevation and the corresponding groundwater elevation to obtain a water head acting on the external surfaces of lining structures. With respect to the determination method of this value, many factors are involved, including the permeability of rocks, the groundwater activity in field, the rock mass structure, etc. In order to fully considered the negative effect, the coefficient is assumed as 1.0, which means no reduction is considered. Such an assumption helps to obtain a most unfavorable situation so as to reserve sufficient safety margin for the lining structures. Based on the geological profile map, a representative tunnel section is selected. The height difference for this section is 263 m. Thus, an external load of 2.63 MPa is considered to applied to the external surface of lining structures.
3.2.4. Swelling pressure. The above laboratory test results show that the expansibility of rocks is significant. A maximum value of measured swelling pressure 550 kPa is adopted. The pressure is applied to the external surface of lining structures to consider the effect of swelling rocks.

3.3. Configurations for numerical calculation

3.3.1. Mesh. The calculation mesh is 200 m long, 120 m wide, and 341 m high (Figure 14). The whole mesh is discretized using hexahedral elements. Totally 311,168 elements and 319,800 nodes are generated.

3.3.2. Initial geo-stress. The initial geo-stress field is determined in vertical stress and horizontal stress, respectively. The vertical stress is directly calculated based on the overburden depth. The lateral stress, according to experiences of practices with similar geological conditions, is determined as 1.2 times the vertical stress. That is, the lateral coefficient is 1.2.

![Figure 14. Calculation mesh](image)

3.3.3. Parameters. The input rock mass mechanical parameters are: deformation modulus 1.3 GPa, Poisson’s ratio 0.39, cohesion 0.12 MPa, and internal friction angle 22 degree. The parameters are obtained through back analysis based on monitored convergence displacement data.

3.3.4. Steps As the lining structures are poured after tunnel excavation, the surrounding rocks of tunnel serve as the host media. Moreover, as a proportion of excavation release load will be applied to lining structures, the calculation steps are arranged as below.

   Step 1: Calculation of initial geo-stress field.
   Step 2: Calculation of tunnel excavation. At this step, the excavation and installation of rock support measures are both considered.
   Step 3: Calculation of lining structure installation. At this step, only the deadweight of lining concrete is considered.
   Step 4: Calculation of lining structures subjected to different load combinations. At this step, the load combinations listed in Table 1 are applied on the lining structures.

Finally, by comparing the calculation results, different design profiles of tunnels can be optimized and recommendations are given. The common software FLAC3D is used to perform the numerical analysis.

3.4. Results

The emphasis of calculation results introduction is placed on lining structures. Table 2 summarized the maximum compressive and tensile stresses in lining structures for different design profiles under various load combinations. It is compared that for type A, B, and C, the stress magnitude becomes smaller as the lining thickness increases. However, even for type C with a lining thickness of 70 cm,
the maximum compressive stress and tensile stress both exceeds the allowable strength value of concrete (19.1 MPa in compression and 1.71 MPa in tension). The type D profile, on the other hand, achieves a satisfactory stress magnitude which does not exceed the designate strength. This indicates that the circular shape of tunnel profile can generate favorable stress distribution and is more reliable for the safety of lining structures. Moreover, by comparing the data obtained by different load combinations, it is discover that the groundwater effect accounts for the primary reason for lining stress. It is probably because the external water pressure is not reduced and the water head at the calculation tunnel section area is considerable. The effect of swelling pressure, based on results from No.3 load combination, is smaller. The effect of excavation load is also minor. In general, as for the studied tunnel section, the effect of groundwater is the biggest and the effect of excavation load is the smallest. Based on comparisons of the stress distribution of lining structures corresponding to different design profiles. It is found that the stress distribution for type A, B, and C are similar. The peak values of compressive and tensile stresses all appear at the intersection area of sidewall and floor, and the inner part of floor. The stress distribution for type D, in contrast, exhibits more uniform distributing characteristic and the peak values are much smaller than other profiles. The stress calculation results are then used for steel reinforcement calculation. It is discovered that the type D only needs a minimum requirement of steel reinforcement, while other types of tunnel profile require higher quantity of steel.

3.5. Design recommendations
Based on above calculation results and their comparison, it is recommended that the type D lining structure is better than other types of tunnel profile. So, type D lining design is selected as the implementation plan.

4. Conclusions
This paper presents a case study on design and profile optimization for tunnel excavated in swelling rocks with water-rich strata. The swelling phenomenon and its inherent mechanism of the concerned rocks are discussed based on laboratory tests and related analyses. The test results are then used to evaluate different tunnel design profiles through numerical simulation. It is compared that the lining stresses are more favorable in a circular tunnel shape, which also helps to reduce steel reinforcement quantity. By comparison, it is worth noting that the effect of groundwater pressure is most significant, the effect of swelling pressure is the second, and the effect of excavation load is the smallest. Moreover, it should be that the above considered loads applied on lining structures are based on certain experiences so their effect ranking largely depends on specific conditions of the studied cases and may be different in other projects. It is promising to further conduct sensitivity analysis regarding these factors. By doing this, their variation laws can be summarized and the findings can be of good reference for tunnel design practices of similar geological conditions.

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