Cause Analysis and Treatment Measures of Tunnel Diseases in Complex Geological Structure with Gypsum-bearing Rock Layers

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Abstract. The length of NL Tunnel in North China is 23.4 km. The ballast bed of the tunnel is a heavy-haul and double-block, ballast-less track. After being completed and opened to traffic, serious diseases such as concrete corrosion, cracking of the lining, deformation of the side wall, and uplift of the track bed were observed. The cumulative length of the disease-carrying tunnel, ~1.4 km, negatively affects the safety of motorists. On-site investigation, theoretical analysis, experimental testing, and numerical calculations, revealed that tunnel diseases result from various factors. That is, owing to the complex geological structure, changes in the volume and quality of groundwater in the gypsum-bearing rock layer were accompanied by special low-temperature sulfate corrosion, rare differential expansion, and significant water-sensitive softening with rheological characteristics. These phenomena eventually resulted in tunnel diseases. Through stability analysis and field practice, an effective set of measures was adopted. These measures included a support structure system combined with near-circular cross sections and buffer layers, a new type of drainage system with special rock layers from inside to outside, and lining structural materials with low-temperature sulfate resistance.

Keywords: Heavy-haul railway; Gypsum-bearing rock layer; Tunnel diseases; Low-temperature sulfate corrosion; Expansion

1. Introduction

With the rapid development of the railway construction in China, an increasing number of projects have focused on tunnels that cross mountains and ridges. Numerous long, large, and deep tunnels have been built. Accordingly, the geological environment of these tunnels is becoming increasingly complex, thereby severely affecting the quality and safety of the construction and leading to different degrees of disease development during the project [1]. Implementing remediation measures for operating tunnels is extremely difficult. Generally, tunnel diseases result from (among others) construction quality defects, groundwater, and special geology [2]. Tunnels with long and large gypsum-bearing rock layers are more prone to diseases during the operation period (compared to tunnels with short and small rock layers). These diseases are mainly manifested as internal crowning and cracking of the lining, arching of the roadbed, and corroding of the concrete. This kind of stratum is characterized by swelling and corrosion to some extent, which affects the stress of the tunnel until diseases emerge with concealment and hysteresis. In addition to the NL Tunnel in North China that...
this work focuses on, similar engineering diseases have been observed in projects of railway and highway tunnels. These projects have been launched in the same or similar environment of geological complexity in areas of North China, West Hubei Province, and West Sichuan Province. Some tunnels, such as the Dugongling Highway Tunnel in Changzhi, Shanxi, the Cross Pass Highway Tunnel in Hubei, the Liangshuijing Tunnel on the Yiba Expressway, and the Baijialing Tunnel on the Chengdu-Kunming Railway, with similar diseases have been reported in the open literature. Similar diseases are observed for other tunnels (absent from the open literature) and most of the cracking and corrosion occur in 3 to 5 years after the construction of the tunnels. This cracking and corrosion pose a significant threat to the construction and operation of these tunnels [3-9].

The engineering characteristics of the Ordovician gypsum-bearing strata in North China and their impact on the project have been extensively investigated. Xiong et al. (2007) [10], investigated via experiments, the engineering characteristics of the gypsum breccia in the Taihang Mountain Tunnel. Hu et al. (2003) [11] conducted studies on the strength characteristics (including the uniaxial strength, triaxial strength, and tensile strength) of special gypsum breccia. Zhang (2006) [12] introduced a construction process and technologies for gypsum breccia tunnels. Zhang et al. (2007) [13] analyzed the pressures and displacement deformations of surrounding rocks during the excavation of gypsum breccia tunnels. Pang et al. (2006) [14] studied the rational cross-section of Taihan Mountain Tunnel in the region of gypsum breccia. The aforementioned have focused extensively on tunnel construction using gypsum breccia with poor strength. However, the engineering properties of the gypsum-bearing strata and the structural pressure characteristics of the tunnel located in these strata remain unclear [15-20].

Under the combined effects of a complex geological structure and groundwater, railway tunnels built on gypsum-bearing strata are vulnerable to diseases including lining cracks, floating arches, and corroding concrete. In this work, based on the disease remediation project of the NL Tunnel, we introduce the pathogenesis, remediation measures, and maintenance effects of these strata, in order to provide reference and data reserves for the construction of similar projects.

2. Tunnel diseases

2.1. Project Overview

NL Tunnel in North China is an electrified double-hole and single-lane tunnel with a total length of 23.4 km and a line spacing of 30 m. The ballast bed is a heavy-haul and double-block, ballast-less track with a section size of 6.5 m x 8.8 m. The tunnel was designed in January 2009, started in April 2010, completed in June 2013, and opened in in January 2015. The tunnel consists of two working zones for organizing the construction: entrance zone (12.9 km construction) and exit zone (10.5 km construction). Limestone, marl, and gypsum breccia are the main strata that the tunnel crosses. The longitudinal section is shown in Figure 1.
2.2. Disease development

In August 2014, lining cracks (76 m on the right line and 54 m on the left line) emerged in the exit working zone for the first time. According to the preliminary analysis, the crack of the structure resulted from the failure of the initial support and water pressure. Demolition of the cracking area and re-implementation of the reinforced concrete structure were decided as a course of action in the meeting. In March 2015, lining cracks appeared in the exit zone of the tunnel. Five severe cracks (51 m in total), which were manifested in the forms of cracking, splitting, reticulate cracking, and squeezing damage to the gutter cover, were observed. The initial assumption was that large horizontal pressure would be generated, owing to factors such as rock softening, swelling, and partial water pressure of groundwater. This would lead to cracking in the second lining side wall of the tunnel. Therefore, the final remediation plan was designed such that the deformation area remained with its initial support. The entire ring of the secondary lining was removed and new reinforced concrete was fabricated for 1050 m up and down rows of the exit zone.

In March 2016, growing cracks were found on both sides of the disease in 2015. Reinforcement measures such as the steel belt stabilization and invert anchor rods were implemented on site.

In March 2017, the problem of track arching appeared in the working zone of the No.5 inclined shaft in the exit zone, thereby affecting the safety of traffic. Subsequently, the scope of disease was further expanded: uplift of the track bed in the No.4 inclined shaft, internal deformation and cracking of the side walls in the No.5 inclined shaft, and lining cracking in the exit zone. The cumulative length of the disease parts in the Tunnel is 1.4 km. A disease length of ~0.13 km, accounting for 6.2% of the 2015 remediation area, reoccurred after the renovation in 2015.
2.3. Characteristics of the diseases

2.3.1 The distribution of the diseases is characterized by segmentation. Tunnel diseases all occurred in the construction zone of the exit. Moreover, the diseases will be more severe in the neighborhood of special geological structures such as faults, slopes, and mine goafs (than in other regions) and when the groundwater supply conditions are good.

2.3.2 Complexity of disease distribution
- The diseases occur in various forms, including uplift of the track bed, cracking of the lining, internal squeezing of the side walls, and rapid corrosion.
- The diseases occur in various strata (including limestone, marl, and gypsum breccia); 29.8\% of the strata contain gypsum.
- The diseases are discovered in both plain concrete structures and reinforced concrete structures.

3. Disease investigation and mechanism analysis

The supplementary investigation included (for example) geological annotation, hydrological survey, cave drilling and geophysical prospecting, geotechnical sampling tests, structure sampling tests, and structural deformation monitoring. During the investigation, 51 holes are drilled, 20 geophysical prospecting lines are installed, and 25 groups of water samples and 56 groups of geotechnical samples are taken. Structures such as syncline cores, faults, and mine goafs have developed in the sections with tunnel diseases. Some local rocks are broken and exhibit uneven hydraulic conductivity, passing through the Fengfeng Formation of Middle Ordovician and Majiagou Formation limestone, marl, intercalated gypsum, and special rock formations of gypsum breccia.

3.1. Construction defects

Of the 33 groups of concrete lining samples taken at the site, 25 groups (75.76\% of the sampling) are characterized by a gypsum content of 0.5\%, which exceeds the standard set in the specification. The highest content and average content are 17\% and 11\%, respectively. When the gypsum (sulfate) content of the aggregate exceeds the standard, the gypsum would react with the hardened cement paste resulting in internal expansion of the concrete. The eroded concrete, which is brittle, loose, and slightly white in color, undergoes further cracking and spalling, leading to failure of the stress-support system. Similarly, defects such as insufficient thickness of the structure and virtual ballast at the bottom of the tunnel are generated. According to the calculations, the structure is weakened by the thickness of the inverted arch and virtual ballast and is destroyed by normal pressure on the surrounding rocks. Along with softening surrounding rocks and increasing external loads, the safety factor of the structure is further reduced.

3.2. Regional contemporary tectonic stress field

The geological structure of the area is complex and has undergone several tectonic movements, which produced various highly complex folding and fractured structures. The burial depth of many regions in the NL Tunnel exceeds 400 m. During the investigation stage, 22 effective tests of crustal stress are performed in four boreholes of CZK4, CZK5, DZK-9, and DZK10 by means of hydraulic fracturing. The results of the tests showed that the stress field in the working area is dominated by a horizontal principal stress and (in general) the magnitude of the field increases linearly with depth. The results also revealed that for the three principal stresses \( SH > SV > Sh \), indicating that the region lies in a state of slip fault. Among 22 test sections taken in the four boreholes, extremely high geostress and high geostress regions account for 86\% and 14\%, respectively, of the measuring points.

Based on the 1:10,000 engineering geological plan of the NL Tunnel, the model is built based on the information concerning the topography, stratigraphic boundaries, faults, and folds to invert the regional ground stresses. The numerical analysis model takes the NL Tunnel as the center line with a
simulation range of 30 km (length) × 22 km (width). The result of the inversion revealed certain characteristics. That is, in the tunnel axis plane and for the entire distribution of the axis, the distribution of the stress in the profile is larger on the west side (inlet end) and smaller on the middle east side (outlet end). This distribution is related to the tunnel depth, which represents one of the crucial factors. Moreover, the high stress section tends to shift eastward. In the plane, the stress on the left side of the line is higher than on the right side, indicating a significant tendency toward imbalance. The above trend is related in some way to the serious diseases at the inlet end and the pronounced difference between the cracks occurring on the left and right walls. Depending on the strength of the surrounding tunnel rocks, the distribution of the strength-to-stress ratio can be obtained by extracting the tunnel axis stress and calculating the strength-to-stress ratio of the surrounding rocks. Figure 3 and Figure 4 show that most sections of the tunnel lie in extremely high stress (83.9%) sections while others lie in high stress (12.3%) and general stress (3.9%) sections. In addition, in the direction of the tunnel axis, some sections of the surface are characterized by a state of tensile stress. This is especially true for sections near the faults that were extended under the action of a contemporary tectonic stress, which induces the infiltration of surface water, thereby accelerating the occurrence of tunnel diseases.

3.3. Hydrated swelling of gypsum-bearing strata

Based on the research and analysis, gypsum-bearing rocks, marl, and gypsum breccia in NL Tunnel exhibit the physical characteristic of water swelling after absorption (as the case of general clay rocks) and hydrated swelling. Under normal temperature and pressure, the interaction between hard gypsum and water is slow, and the water-absorbing-and-swelling time may last 3 to 5 years. The hydrated-
swelling rate of hard gypsum in gypsum-bearing rocks is slow and the process may continue for years or even longer, and is accompanied by expansion and deformation. Investigation stage: a maximum free swelling rate of 25% is measured for the easily disintegrated rocks. Moreover, a maximum rate of 2.58% is measured for the non-disintegrated rocks, which are non-swelling rocks, which exhibit certain swelling characteristics. Remediation stage: During the supplementary investigation and emergency rescue stages of the South Lvliangshan Tunnel, the swelling ability exhibited by 215 sets of perimeter rocks is investigated. The results showed that only three sets of perimeter rocks can be considered weak swelling rocks, based on the Code for Special Soil and Rock Investigation of Railway Engineering. The other rocks failed to meet the inflation criterion.

**Table 1.** Test data revealing the swelling ability of gypsum-bearing rocks

| Composition            | Time   | Saturated Water Absorption Rate | Free Swelling Rate       | Swelling Strength                  |
|------------------------|--------|--------------------------------|--------------------------|-----------------------------------|
|                        |        | 0%–24.5% (One sample set >10% in nineteen sets) | 0%–49% (Two sample sets >30% in nineteen sets) | 202.78 kPa (Detected in one sample set of nineteen sets) |
| Gypsum breccia         | 2015   | -                              | -                        | -                                 |
|                        | 2017   | -                              | -                        | -                                 |
|                        | 2015   | 0.57%–17.96% (One sample set >10% in fifteen sets) | 0%–191% (One sample set >30% in twenty sets) | 19.21 kPa–462.2 kPa (Three sample sets >100 kPa in twenty sets) |
| Gypsum-bearing marl    | 2017   | 0.29%–6.30% (All eight sample sets <10%) | 0%–172% (Five sample sets >30% in fifteen sets) | 1 kPa–415 kPa (Two sample sets >100 kPa in eleven sets) |
|                        | 2015   | 0.12%–7.31% (All sixteen sample sets <10%) | -                        | -                                 |
| Marl (rocks)           | 2017   | 0.92%–3.88% (All eighteen sample sets <10%) | 0%–221% (Three sample sets >30% in twenty six sets) | 1 kPa–1130 kPa (Two sample sets >100 kPa in eighteen sets) |

Due to the hysteresis associated with the swelling characteristics of gypsum-bearing rock, the existing test methods may be ineffective in determining the swelling characteristics. In fact, weak to moderate swelling in local sections of the gypsum-bearing strata may occur. The existing codes provide no method for the calculation and design of the additional load generated by the action of swelling.

3.4. Environmental corrosion and groundwater changes

The hydrogeological conditions in the NL Tunnel area are complex. Water collection in the mine goaf and faults provide favorable conditions for the redistribution of groundwater in the tunnel and the occurrence of diseases is closely related to the development degree of groundwater. During the construction phase, the tunnel is free of water, and with improvements in the ecological environment in recent years, the opening of the tunnel has changed the seepage field of the groundwater. Moreover, the drainage system in the tunnel has basically failed, and seasonal underwater converges around the tunnel through faults and penetration cracks. The concentration of sulfate ions increases rapidly, owing to poor drainage and the chemical reaction of the gypsum-containing strata. Furthermore, special carbon sulfur calcium silica corrosion (as revealed by concrete tests) leads to an increase in the severity of the corrosion.
Sulfate ions and ordinary Portland cement are most conducive to the formation of thaumasite at low temperatures (i.e., temperatures below 15°C), which significantly reduces the strength of the concrete. Tests have revealed that the time for damage to the thaumasite decreases with decreasing ambient temperature. After long-term observation, the annual temperature in the NL Tunnel ranges from 8°C to 15°C, which is most conducive to the occurrence of thaumasite-type damage to the concrete.

3.5. Analysis of disease mechanisms

Based on the above findings, taking tunnel support structure as the object of analysis, the causes of diseases were attributed to both internal and external factors. The external factor is the swelling strength generated by the hydration of the gypsum-bearing rock strata. Similarly, the internal factor is the corrosion of the thaumasite produced by the excess sulfate of the initial tunnel and the second lining concrete aggregate.

3.5.1 External cause of swelling

Hard gypsum in gypsum rocks is prone to hydration when exposed to water and can be transformed into gypsum that contains two crystal waters. During the process, the volume of gypsum increases, and theoretically, the volume of solids increases by 58% corresponding to swelling of the gypsum. Gypsum breccia and gypsum-bearing breccia marl contain hydrophilic minerals (such as gypsum and montmorillonite) and are therefore susceptible to swelling and disintegration in water. Tunnel excavation alters the original stress state of the ground. The gypsum-bearing strata form the force of swelling when they encounter water, and the structural stress field controls the swelling force direction and provides conditions for surface water infiltration in special structural sections. When the horizontal swelling force of the strata exceeds 380 kPa, the tunnel lining structure will crack. The difference in the rock swelling force test results may be attributed to three factors. First, the possible effect of differences in the structural configuration of the rock on the test results is neglected. Second, the method recommended in the rock test protocol differs from that of the consolidation apparatus method: in the test, the samples are processed prior to being placed in the test vessel and then immersed in water for the swelling experiment. The problem with this method is that when placing a rock sample in a vessel, gaps occur between the sample and the vessel. The gaps provide space for swelling and deformation of the rock, which leads to a relatively discrete swelling force generated during the test. Finally, the tests suggest that, under normal temperature and pressure, the interaction speed between hard gypsum and water is slow, and the swelling time of absorption may last three to five years. Regarding the swelling test of hard gypsum rock, the swelling force of the rock requires significant measuring time depending on the method suggested by the protocol or the consolidation apparatus.
3.5.2 Internal cause of corrosion
In contrast to conventional sulfate attack, thaumasite corrosion leads to only slight swelling and cracking of the concrete macroscopic volume, but directly results in the decomposition of CSH gel in the cement stone. This decomposition transforms the concrete into a kind of pulpy mud-sand mixture with low strength. Observing and recognizing the corresponding strong concealment and destructiveness in the early stage are difficult. The chemical reaction formula of the supporting structure concrete undergoing corrosion by low-temperature sulfate is given as follows:

\[
4Ca^{2+} + Si(OH)_4 + 2HCO_3^- + SO_4^{2-} + 2OH^- + 10H_2O \rightarrow Ca_3[Si(OH)_4 - 12H_2O](SO_4)(CO_3)_3 + CaCO_3\]

Five basic conditions are required for sulfate erosion of concrete at low temperature: SO_4^{2-}; SiO_2; CO_3^{2-}; water; and low temperature. In the local area where corrosion occurred in this tunnel, these basic conditions for thaumasite type of sulfate erosion were met under the environmental conditions of the surrounding water, soil, and structural concrete. The corrosion of the concrete led to the failure of the initial tunnel support as well as a local loss of strength and cracking of the secondary lining.

4. Remediation measures
A remediation plan is proposed to address problems such as structural stress, swelling, corroding, and the softening effect of groundwater. This plan includes strengthening the supporting structure, improving the durability, and implementing measures of waterproof and drainage from both internal and external.

4.1. Strengthening of the supporting structure

Nineteen working conditions are calculated for the original tunnel section considering the swelling load on the surrounding rocks, and the unfavorable condition of the horizontal swelling force on the side walls. The original design reinforced concrete section, when the swelling force exceeds 380 kPa, has a safety factor exceeding the standard safety value of 2.4, indicating that the force on the arch foot position is concentrated. When the swelling force of the original designed plain concrete section exceeds 92 kPa, the tunnel side walls will crack and deform.

The original tunnel structure is characterized by a harsh tunnel environment, complex geological structure, and special stratigraphic nature. Regarding remediation, this structure is first considered demolished and rebuilt with a structural section that can withstand greater external forces (than previous forces). Numerous calculations and analyses are performed using finite element software. The results suggest that the side walls can be enlarged and the inverted arch curvature can be enhanced by adopting a form of polycentric or circular and a composite lining structure with an inverted arch. The calculations consider a Type AA section (circular), Type A section (sub-circular), Type B1 section (75 cm excavated the side wall), Type B2 section (50 cm excavated the side wall), and Type B3 section (38 cm excavated the side wall). The final measures are determined (see below) after consideration of the horizontal load capacity.

① For stress-concentrated locations with poor geological conditions, swelling force, and tectonic stress, a Type AA section is used with a lining thickness of 70 cm, which can withstand a horizontal swelling load of 1.1 MPa (maximum value of the test data).

② For locations with poor geological conditions and general swelling force, a Type A section is adopted with a lining thickness of 55 cm, which can withstand the horizontal swelling load of 0.65 kPa.

| Table 2. Force Calculation Results for Different Types of Sections |
|---------------------------------------------------------------|
| Types of lining sections | Maximum swelling force (horizontal) | Maximum swelling force 1130 kPa Calculation | Safety factor | Least favorable position | Cross-sectional profile area (55 cm thickness) |
|--------------------------|-------------------------------------|---------------------------------------------|--------------|--------------------------|-----------------------------------------------|
| Types of lining sections | Maximum swelling force (horizontal) | Maximum swelling force 1130 kPa Calculation | Safety factor | Least favorable position | Cross-sectional profile area (55 cm thickness) |
|--------------------------|-------------------------------------|---------------------------------------------|--------------|--------------------------|-----------------------------------------------|

8
### Table

| Type   | Pressure (kPa) | Horizontal Effect | Circular Effect | Reinforcement | Side Walls, Arch |
|--------|----------------|-------------------|-----------------|---------------|-----------------|
| AA     | 850            | Lining thickness 700, 25@150 | Lining thickness 500, 25@150 | 2.8           | 81.71           |
| A      | 650            | 25@150;            | 600, 25@150     | 2.6           | 69.91           |
| B1     | 510            | Lining thickness 900, 25@150 |                 | 2.6           | 65.8            |
| B2     | 450            | Lining thickness 850, 25@150 |                 | 2.6           | 65.5            |
| B3     | 420            | Lining thickness 1000, 25@150 |                 | 2.6           | 63.2            |

**Figure 6. Type AA Section**

**Figure 7. Type A Section**

### 4.2. Durability improvement

Based on the microscopic observation results of the damaged concrete (Figure 8), the cementitious material within the concrete is already needle-flocculent. Preventing the low-temperature sulfate erosion of concrete should be performed from two perspectives. On the one hand, the possibility of sulfate erosion from the source can be reduced via measures such as diverting and directing water inrush from the surrounding rock. On the other hand, the resistance of concrete to sulfate erosion must be improved.

- Original supporting structure: use C25 wet-sprayed impermeable concrete and polycarboxylate-type high-performance superplasticizer and alkali-free liquid accelerator as additives; use sulfate-resistant cementitious slurry to backfill the back of the initial support.
- Second lining structure: improve the grade and impermeability of the second lining by adopting C45 and P10 reinforced concrete.
- Mix proportion study: mix finely ground slag (recommended dosage: 40%–50%) and silica fume into the lining concrete to improve its resistance to the erosion of thaumasite-type sulfate; use siliceous aggregate instead of limestone aggregate to reduce the risk of concrete being eroded by thaumasite-type sulfate (granite, basalt).
• Ground water isolation: set up an all-inclusive waterproof layer with a drainage system in the outside in order to reduce the contact between groundwater and the supporting structure; waterproof materials should meet the requirements of sulfate corrosion resistance; the gutter should be treated with anti-corrosive asphalt coating.

4.3. Internal and external measures of waterproof and drainage

4.3.1 Waterproof measures
For grouting waterproof, use full-ring radial grouting to seal cracks in broken surrounding rocks and reduce the infiltration of ground water (grouting range: 8–10 m outside the tunnel). Regarding the waterproof board, use anti-sticky EVA and all-inclusive waterproof board to prevent the longitudinal flow of ground water as well as the contact between ground water and the lining. Concrete self-waterproof is realized by using C45 corrosion-resistant waterproof concrete to improve the self-waterproof function of the second lining.

4.3.2 Drainage measures
For the drainage board, a circular concave-convex drainage board is installed between the waterproof board in the tunnel and the geotextile to enhance the drainage capacity between the waterproof board and the initial support. For the blind-pipe drainage, use the longitudinal anti-crystallization ring blind pipe for drainage. Increase the diameter of the pipe comprising the longitudinal ring in the tunnel and increase the distance among the pipes of the encrypted ring in order to prevent the blockage of crystals. For the drainage pipe, insert a horizontal drainage pipe through the waterproof board at the position of the low side wall to solve the problem of water accumulation behind the board. For the flat guide drainage hole, use flat guides to set up drainage holes around the main tunnel in order to reduce the impact of groundwater on the main tunnel.

Figure 8. Scanning electron micrographs showing concrete damage
5. Maintenance effect

Key monitoring was performed in the sections with poor lithology (broken rock masses, soft rocks, water swelling and softening), complex geological structure (distribution of fissures and faults), developed groundwater, and serious diseases of the original tunnel. A total of 32 typical monitoring sections were laid out, including measurements of deformation and stress. Typical results of monitoring are shown in Figure 10 to Figure 12.

After sidewall excavation and implementation of the initial support, the clearance displacement of the tunnel and the pressure between the surrounding rocks and the initial support layer will increase rapidly in a short time (5 to 10 days). This results from the stress release of the surrounding rocks. After this rapid increase, the displacement stabilizes gradually. Excavation and construction of the inverted arch and the construction of the second lining will lead to a small sudden increase in both the displacement and the pressure.

The pressure between the initial support of each measuring point and the second lining layer is generally very low. This pressure is far smaller than the pressure between the ultimate bearing capacity of the Type A (near-circular section) section lining structure, indicating that the current lining structure still has a large bearing reserve.
6. Conclusions and suggestions

Diseases including lining cracking, sidewall internal squeezing, track bed uplift, and concrete corrosion, which threaten the safety of railway operation after the construction of the NL Tunnel, are analyzed in this work. Various methods including field testing, indoor testing, numerical simulation, and theoretical analysis, are employed for systematically determining the causes and remediation measures of the diseases. The main conclusions can be summarized as follows:

(1) The occurrence of tunnel diseases has a complex structural geological background. Strata with gypsum-bearing limestone, marl, and gypsum breccia are affected by changes in the quality and quantity of groundwater. These changes result in the special corrosion of sulfate at low temperatures, rare differential swelling, and the rheology of significant water-sensitive softening on surrounding rocks with hysteresis and progressivity. The coupling effect of lithology and groundwater leads to diseases, whose scale and the degree of damage to the lining structure are rare at home and abroad.

(2) Based on the research and analysis of the lining-structure stability, the present work proposes the establishment of a system where a reinforced supporting structure for near-circular sections is
obtained. A new waterproof and drainage system for special rock strata is also proposed. Additionally, targeted measures such as improving the low-temperature sulfate corrosion resistance are suggested for lining structural materials.

(3) Based on the monitoring data and the operating conditions, the current tunnel as a whole is stable and the lining structure is safe.

(4) The occurrence of diseases in the NL Tunnel results mainly from the deficiency in the development of professional technologies and relevant regulations. A thorough understanding of potential tunnel disease, especially the appearance and development of diseases caused by environmental changes after tunnel excavation, is lacking. Further studies are required for determining the action modes, classifications, and grades of the tunnel swelling load, and developing the test methods for assessing the swelling rocks.
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