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Research on Systematic Investigation and Multi-dimensional Treatment of Tunnel Diseases in the Sichuan-Xizang Highway Tunnel

Faqiu Zhang*, Yifei Tong, Liangkun Xie, Chengrui Yao, Yi Zhang

China Merchants Chongqing Testing Center for Highway Engineering Co., Ltd., Chongqing 400067, China

Author to whom correspondence should be addressed.

Abstract: In this paper, the typical diseases of 17 tunnels in the Zhubalong to Dongjiu section of the Sichuan-Xizang Highway on the National Highway 318 were systematically investigated and analyzed in depth. The investigation results show that the tunnel diseases mainly include the hollowing out of the foundation of the riverside side of the open-cut tunnel, the leakage of the lining (point, line, surface, and construction joint seepage), the lining cracks, the pavement cracks and seepage, and the blockage of the drainage system. Based on the causes of the disease, this paper proposes a multi-dimensional treatment design scheme covering the hole, lining, pavement, and drainage system. It is verified by field implementation that the proposed treatment measures effectively control the development of the disease, significantly improve the operation status of the tunnel, and achieve good engineering results. This study provides valuable engineering practice experience and reference for the accurate diagnosis and efficient treatment of tunnel diseases under similar complex geological conditions of the Sichuan-Xizang Highway.

Keywords: National highway 318 line; Sichuan-Xizang Highway; Tunnel disease; Multi-dimensional treatment; Engineering practice

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1. Introduction

As a key node of highway traffic, the operation safety and durability of tunnels are very important. However, under complex geological and climatic conditions, tunnel diseases occur frequently, which seriously affect traffic safety and structural stability. The geological and hydrological conditions of the Zhubalong to Dongjiu section of the Sichuan-Xizang Highway on the National Highway 318 are complex, which makes the tunnel disease problem in this area particularly prominent. Therefore, it is urgent to carry out systematic investigations, in-depth analyses, and put forward effective treatment schemes for tunnel diseases in this area to ensure the smooth and safe operation of highways.

According to the inspection results, the current tunnel diseases are mainly reflected in the damage of the portal, the damage of the lining structure, the leakage of the lining, the leakage of the pavement, and so on. In view of the hollowing out of the bottom of the foundation of the open-cut tunnel, Zhu Chang'an et al. proposed the use of an anti-erosion pile foundation, and reserved the channel for debris flow, which can avoid the tunnel foundation being hollowed out and lead to overall instability [1]. In view of the lining structure disease, Wang Yunshan put forward different treatment methods, such as crack repair glue, riding crack grouting, chiseling, and filling slurry for cracks of different widths [2]. According to the degree of tunnel crack damage, Yang Chaoshuai et al. proposed measures such as steel fiber reinforced concrete reinforcement, steel strip reinforcement, and crack grouting reinforcement [3]. Song et al. studied the repair materials of concrete structures [4]. The study found that cement-based materials have good mechanical properties and good compatibility with the concrete matrix, and polymer-modified materials show lower shrinkage and higher flexural strength, which provides a basis for the selection of crack treatment materials.

For tunnel leakage, He proposed the combination of water plugging and drainage in the tunnel, using polyurethane water plugging and an open stainless steel drainage box to connect water [5]. Yan et al. reviewed the new achievements of polymer grouting materials in the treatment of tunnel leakage, introduced the properties and applications of various modified polyurethane and epoxy resin grouting materials, and Kong evaluated the application effect of cement-based anti-seepage coatings in highway tunnels [6–7].

Pavement seepage is usually caused by the blockage of tunnel drainage facilities. Zhu et al. proposed to avoid the accumulation of water in the lower part of the road to the central ditch by setting up vertical collecting wells and horizontal drainage blind ditches [8]. Through field investigation and sampling analysis, Ma et al. revealed the mechanism of crystallization blockage in the tunnel drainage system, and put forward treatment measures such as increasing side wall drainage holes and well point dewatering holes, and changing drainage ditches to open ditches according to the characteristics of diseases [9]. These studies provide important theoretical and technical support for tunnel disease treatment.

However, the existing research mostly focuses on the treatment technology of a single disease, and lacks the "whole chain" research and practical verification of the systematic and comprehensive investigation, cause analysis, and treatment scheme of tunnel diseases under the extremely complex geological and climatic conditions of the Sichuan-Xizang Highway. The purpose of this paper is to form a closed loop of demonstration through the following aspects based on the disease treatment project of Zhubalong to Dongjiu section of Sichuan-Xizang Highway on National Highway 318: Firstly, the disease types and distribution of 17 tunnels in this section are systematically investigated. Secondly, the formation mechanism of various diseases is deeply analyzed, and a set of targeted and operable treatment design schemes is proposed based on the causes of diseases. Finally, the effectiveness of the proposed scheme is verified by the preliminary feedback of field implementation. The results of this study not only provide technical support for the project, but also hope to provide valuable reference experience for the accurate diagnosis and efficient treatment of tunnel diseases in similar complex environments.

2. Project profile

The tunnel site area belongs to the plateau monsoon climate, which has the climatic characteristics of high cold, rainy, and snowy, and is an important cause of tunnel diseases. There are 17 tunnels in the range of

Zhubalong to Dongjiu section of Sichuan-Xizang Highway on National Highway 318, which need to be treated (including 5 dark hole structures, 11 open hole structures, and 1 shed hole structure). Through field investigation, it is found that the main diseases of the tunnel are hollowing out at the bottom of the foundation of the open hole, lining leakage, lining cracks, pavement cracks, pavement seepage, drainage ditch blockage, and water accumulation. The tunnel site disease is shown in **Figure 1**.

(a) The bottom of the foundation of the portal is hollowed out

(b) Water seepage marks on the lining surface

(c) Inspection of well water accumulation

(d) Pavement seepage

Figure 1. Tunnel disease scene photos

3. Disease analysis

3.1. Cause analysis of hole disease

The main disease at the entrance of the tunnel is the hollowing out of the bottom of the foundation on the riverside side of the open-cut tunnel. The causes are complex, mainly including: (1) Hydraulic erosion: the large amount of sediment carried by the river in the flood season and the continuous erosion of the foundation lead to the gradual hollowing out of the bottom of the foundation. (2) Construction quality defects: the base cleaning is not complete, and the degree of compaction is insufficient. (3) Insufficient design consideration: The design specification of the highway tunnel clearly stipulates the structural design of the tunnel portal [10]. In the design stage of foundation structure, if the local complex hydrogeological conditions, extreme water flow scouring force, or insufficient foundation depth are not fully considered, the foundation itself will not have enough ability to resist scouring, which will induce the phenomenon of bottom hollowing. In summary, the treatment scheme of the hole disease should be based on the enhancement of the anti-scouring ability and structural stability of the foundation, which provides a theoretical basis for the subsequent design of the anti-scouring wall and the stone lead cage.

3.2. Cause analysis of lining disease

Lining diseases mainly include water leakage and cracks. The causes of lining leakage are as follows: (1) Abundant groundwater and permeability of surrounding rock: the development of joints and fissures in the surrounding rock of the tunnel site, the large amount of ice and snow melt water and atmospheric precipitation recharge, resulting in increased leakage; (2) Failure of waterproof system: the tunnel waterproof layer is damaged or aged, so that the groundwater bypasses the waterproof layer and directly enters the back of the secondary lining; (3) Blockage of drainage system: if the drainage system inside the tunnel accumulates water behind the lining due to sediment deposition or freezing, forming water pressure, forcing groundwater to seep from the weak parts of the lining or construction joints, and may cause water accumulation in the inspection wells. Therefore, the treatment strategy of lining leakage water needs to comprehensively consider blocking the water source, repairing the waterproof layer, and ensuring smooth drainage, which provides a design basis for subsequent measures such as grouting, painting waterproof coating, and drilling and drainage for different leakage types.

Causes of lining cracks: (1) Complex geological conditions and foundation deformation: uneven soft and hard surrounding rock, faults, or weak interlayers lead to uneven settlement. This foundation deformation will generate additional stress in the lining structure. When the stress exceeds the tensile strength of the concrete, cracks will be formed. (2) The effect of mountain bias: an asymmetric mountain leads to an asymmetric distribution of surrounding rock pressure, and the formation of mountain bias leads to uneven stress of the lining structure, resulting in eccentric load, which in turn leads to local stress concentration, resulting in lining cracking and even structural damage. (3) Construction quality defects: the backfill behind the lining is not dense, or the pouring thickness is insufficient. Under the action of external load, these weak areas are prone to stress concentration, resulting in cracking. In view of the complexity and diversity of the causes of lining cracks, the treatment scheme should take targeted measures according to the type, width, depth, and specific causes of cracks, so as to effectively restore the integrity and durability of the lining structure.

3.3. Cause analysis of pavement disease

Pavement diseases mainly include pavement cracks and pavement seepage. The causes of pavement cracks are as follows: repeated traffic loads lead to fatigue failure of pavement structure, and internal damage accumulation of materials forms through cracks; temperature shrinkage stress aggravates crack development. The treatment needs to close the cracks and prevent water vapor intrusion.

The causes of pavement seepage are as follows: (1) Groundwater upwelling: groundwater upwelling seeps through construction joints or weak parts of cracks; (2) Pavement structure defects: pavement concrete segregation, insufficient vibration to form honeycomb holes, providing a channel for groundwater or surface water to penetrate the pavement; (3) Drainage system failure: improper design or failure of drainage facilities, resulting in the accumulation of water under the road cannot be discharged in time. Therefore, the treatment scheme should comprehensively consider cutting off the water source, repairing the pavement structure defects, and ensuring the smooth drainage system, so as to achieve a complete solution to the problem of pavement seepage.

3.4. Analysis of the causes of drainage system diseases

The main diseases of the tunnel drainage system are drainage ditch blockage and water accumulation. The main causes include: (1) Design and construction defects, the slope of the drainage pipe is not consistent with the longitudinal slope of the tunnel, which leads to siltation; (2) Sediment and mineral deposition: long-term deposition of sediment minerals narrows the pipeline section; (3) Waterproof system failure and flow around: The failure of the waterproof system leads to the flow of groundwater carrying sediment into the pipeline. Therefore, the treatment plan should focus on regular dredging, optimizing the drainage slope, and checking and repairing the waterproof system to ensure the normal operation of the drainage function.

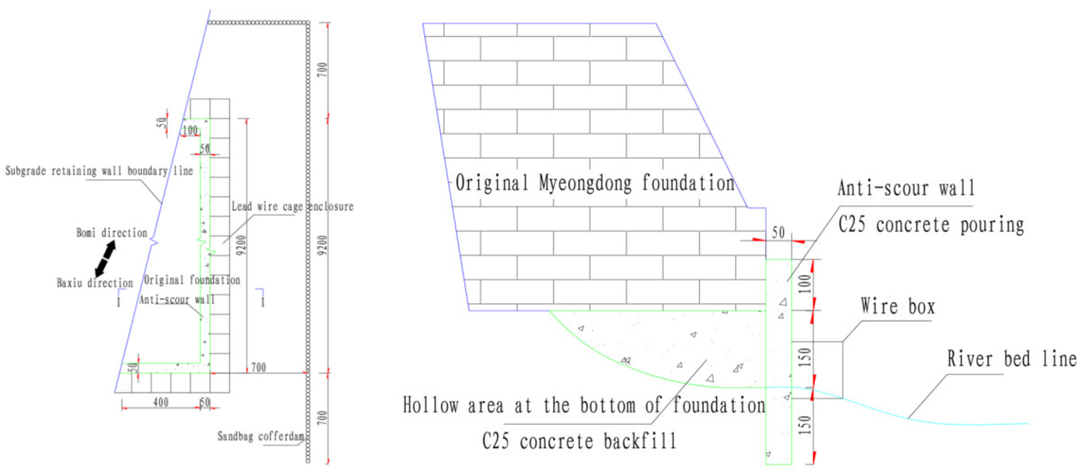
4. Treatment design for disease

4.1. Treatment of hole disease

In view of the hollowing out of the bottom of the foundation at the riverside side of the open-cut tunnel, the treatment is carried out by adding an anti-scour wall and a block stone lead wire cage.

The specific construction process is as follows: (1) Cofferdam: construction in dry season, 7 m extension along the direction of the river as the cofferdam, using sandbags to fill, height of 1.5 m, select the site sand as filling material; (2) Excavation foundation: after the cofferdam, clean up the bottom of the mud, along the foundation around the deepening of the excavation, the foundation width of 50cm, the depth of the original foundation according to the above 1m, 3m below or into the riverbed at the bottom of the bedrock is not less than 0.5m control. (3) Wall pouring: then use C25 concrete to pour the wall, and backfill the cavity area at the bottom of the foundation of the open-cut tunnel; (4) Lead wire cage enclosure: Finally, a ring of stone lead wire cage enclosure is placed along the outer side of the scouring wall. The size of the lead wire cage is 1 × 1 × 1.5 m (length × width × height), the diameter of the wire cage is 6cm, and the diameter of the wire is 2.5 mm, so as to reduce the scouring effect of the river water on the bottom of the scouring wall.

At present, there is an obvious suspension in the section of the open-cut tunnel. It is suggested that the settlement monitoring of the end wall of the open-cut tunnel should be carried out before construction. If there are abnormal conditions, traffic control should be carried out in time to ensure the safety of driving. The design of the hollowing treatment at the bottom of the foundation of the open-cut tunnel is shown in **Figure 2**.



(a) Foundation plan (b) I-I profile

Figure 2. Design drawing of hollowing treatment at the bottom of the open-cut tunnel foundation

4.2. Lining disease treatment

4.2.1. Lining leakage water treatment

(1) Point seepage treatment: Drilling (14 mm, 20cm deep), pressure injection, polyurethane grouting material. The treatment construction sequence is to find the water leakage point → drilling → high-pressure air cleaning hole → use the sealing glue to install the grouting nozzle → pressure grouting material → remove the grouting nozzle. The design of point seepage treatment is shown in **Figure 3**.

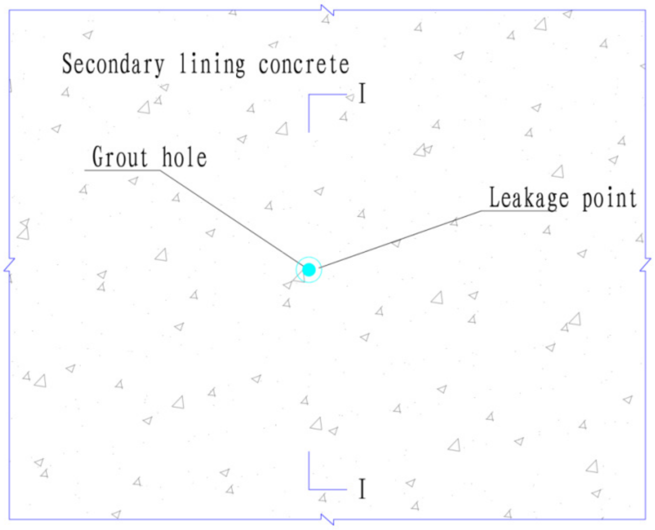


Figure 3. Design of point seepage treatment

(2) Seam seepage treatment: Drilling (14 mm, 20 cm deep, spacing 30 cm), pressure injection of polyurethane grouting material, and then brushing sealing glue, brushing cement-based permeable crystalline waterproof coating.

The construction sequence of the treatment is to find leakage water cracks → drilling → high-pressure air cleaning → grouting → removing the glue nozzle → cleaning the surface → painting waterproof coating. The design of the seam seepage treatment is shown in **Figure 4**.

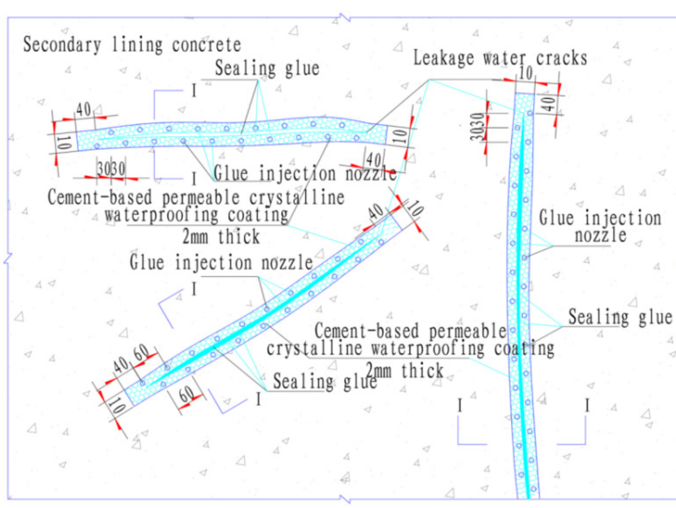


Figure 4. Design of slit seepage treatment

(3) Surface seepage treatment: Drilling (plum-shaped arrangement, spacing of 50 cm, 14 mm, depth of 20 cm), pressure injection of polyurethane grouting material, coated with cement-based permeable crystalline waterproof coating (coating area expanded by 20 cm). The construction sequence of the treatment is the same as above. The surface seepage treatment design is shown in **Figure 5**.

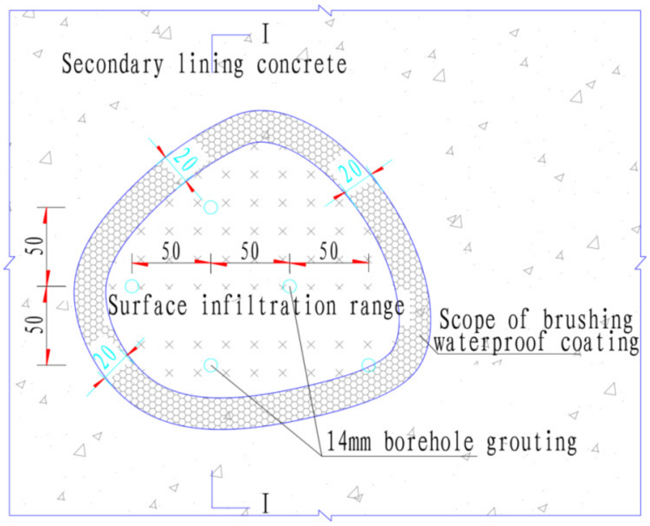


Figure 5. Plane seepage treatment design

(4) Side wall drilling drainage treatment of the serious seepage section: For the serious water seepage section, after drilling holes into the lining at the foot of the lining side wall, the groove is drilled, and the buried pipe is used for drainage. The main construction steps are as follows: determining the section → drilling the side wall foot (φ60 mm, 1.5 m long, 1 m deep into the surrounding rock) → drilling the inner side wall of the cable trench, burying the φ50 mm drainage steel wire hose → connecting with the pre-buried drainage pipe or the side trench. The design of the side wall foot drilling drainage treatment is shown in **Figure 6**.

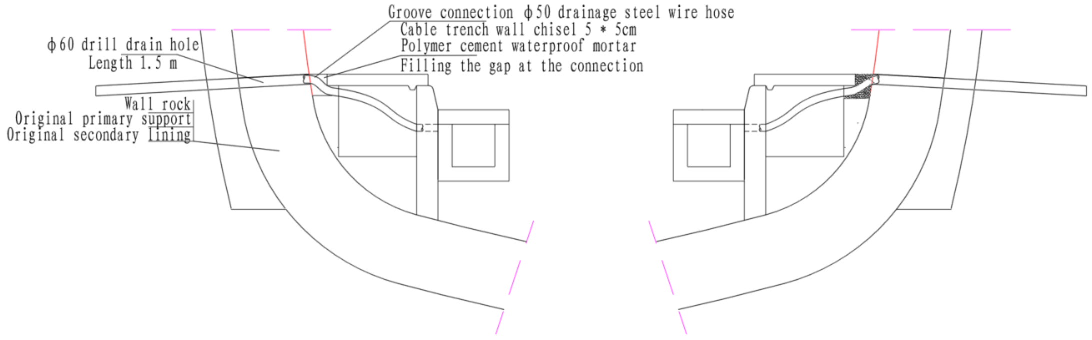


Figure 6. Design drawing of the side wall foot drilling drainage treatment

4.2.2. Treatment of lining cracks

Using surface sealing method: (1) Observe the crack state; (2) Base treatment-clearing dust and oil, steel wire brush cleaning debris, acetone cleaning; (3) Brush crack sealant, width 5 cm, thickness not less than 2 mm.

4.3. Pavement disease treatment

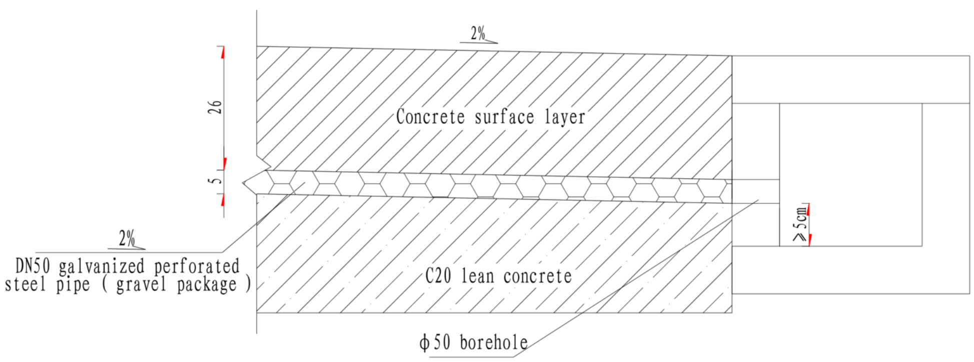
4.3.1. Pavement crack treatment

For the slightly cracked sections of the pavement, the cracks are treated by filling and closing. The surface sealing construction technology of pavement cracks is as follows: (1) Remove the loose crack edge; (2) remove debris and dust in the seam; (3) fill the seam with epoxy resin and tamping; (4) flatten the repaired surface.

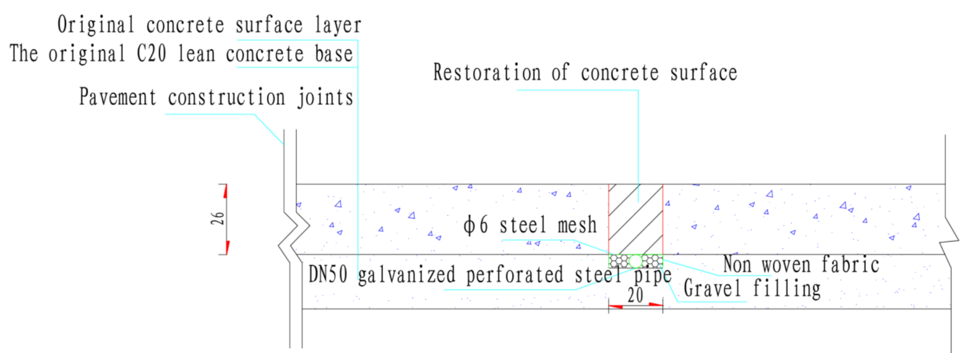
4.3.2. Pavement seepage treatment

In view of the seepage situation of the tunnel pavement, the method of chiseling the buried pipe to introduce seepage into the side ditch is adopted for treatment.

The specific measures are as follows: (1) grooving 20 cm × 31 cm (to the pavement base); (2) DN50 mm drainage pipe is laid at the bottom of the groove, the slope is 2%, and the distance between the bottom of the pipe and the bottom of the side ditch is not less than 5 cm; (3) gravel cover, wrapped seepage geotextile anti-blocking, above the Φ6 mm steel mesh (spacing 5 cmx5 cm, width 20 cm); (4) Drilling φ50 mm connected side ditch at the side ditch; (5) C35 concrete to restore the road. The design of pavement seepage treatment is shown in **Figure 7**.



(a) Large sample drawing of drainage pipe leading into side ditch



(b) Drainage pipe into the side ditch section diagram

Figure 7. Design drawing of pavement seepage treatment

4.4. Treatment of drainage system diseases

(1) Treatment of road drainage ditch blockage: The treatment is carried out by manual cleaning and

dredging.

(2) Treatment of blockage of the central drainage ditch and transverse drainage blind pipe: The combined pipeline is used to dredge the high-pressure flushing of the sewage suction vehicle, and the electric dredger is rotated and inserted into the open pipeline; the cable wearer pulls the sediment back and forth, and dredges it repeatedly until it is completely unblocked.

(3) Vertical drainage pipe inspection and well drilling water diversion treatment: First, try to dredge the transverse diversion pipe; if it cannot be dredged, a hole is drilled between the inspection well and the cable trench, and the side trench is connected with a hose (if there is a pre-buried drain pipe, it is connected, otherwise the hole is led to the side trench). The design of vertical drainage pipe inspection and well water treatment is shown in **Figure 8**.

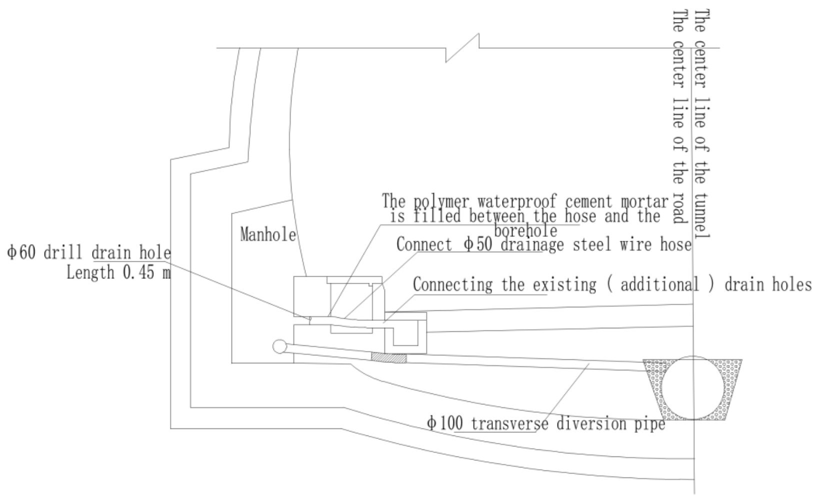


Figure 8. Design drawing of vertical drainage pipe inspection and well water treatment

5. Discussion and outlook

In this paper, the systematic investigation, cause analysis, and treatment design of the tunnel diseases from Zhubalong to Dongjiu section of Sichuan-Xizang Highway 318 are carried out. The field implementation shows that the treatment measures have achieved good engineering results and effectively controlled the development of the disease.

At present, the evaluation of treatment effect is mainly based on on-site qualitative observation and short-term feedback. There is a lack of long-term quantitative monitoring data (water seepage, crack width change, structural settlement, etc.), and quantitative demonstration has limitations. This is also the direction that future research needs to focus on. In order to further improve this study, future work will focus on the following aspects:

(1) Establish a long-term monitoring system: sensors are arranged in the treatment area to monitor the key indicators such as water seepage, lining deformation, and pavement condition for a long time and continuously, and obtain quantitative data;

(2) Quantitative evaluation of treatment effects: Based on long-term monitoring data, statistical methods and engineering evaluation models were used to scientifically evaluate the long-term effectiveness and

durability of different treatment measures.

(3) Promotion, application, and experience summary: The experience of this study is extended to tunnel projects in Sichuan-Xizang Highway and other similar areas to form a more universal disease treatment guide. Through the above efforts, it is expected to form a complete closed loop from disease diagnosis, treatment design, implementation, to effect evaluation and feedback, and provide a more solid scientific basis for the long-term safe operation of tunnel engineering.

6. Conclusion

In this paper, a complete demonstration chain of disease investigation-cause analysis-treatment design-preliminary effect verification is constructed for 17 tunnels in the Zhubalong to Dongjiu section of the Sichuan-Xizang Highway on Line 318. The main conclusions are as follows:

(1) Systematic investigation identified the types of diseases: open-cut tunnel foundation hollowing, lining leakage (point, linear, planar, and construction joint leakage), lining cracks, pavement cracks and leakage, drainage ditch blockage, etc.

(2) Disease mechanism: the hollowing out of the open cut tunnel foundation is related to river erosion, improper construction, and insufficient design; the leakage of lining is related to the joint of surrounding rock, waterproof damage, and drainage blockage. Lining cracks are related to geological conditions, mountain bias, and construction defects.

(3) A multi-dimensional treatment design scheme covering the hole, lining, pavement, and drainage system is proposed. The effectiveness is verified by field implementation, which significantly improves the disease condition and shows a good engineering effect. It provides practical experience and technical reference for the treatment of tunnel diseases in the Sichuan-Xizang highway and similar complex geological environments, and initially forms a closed loop from problem discovery to disposal scheme implementation.

Disclosure statement

The authors declare no conflict of interest.

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