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# Optimizations for tunnel drainage water system based on locations of crystallizations

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**ABSTRACT**

Crystalline blockages are common disease in tunnel drainage systems. In order to optimize the tunnel drainage system, it is necessary to identify the locations that are prone to crystallization. This paper recorded the quantity and the locations of the crystallizations in over ten tunnels in operation period along Renxin Expressway and Yinghuai Expressway in Guangdong Province. The crystal samples were taken from different locations to analyze their micromorphology through X-ray diffraction and scanning electron microscopy. The results show that tunnel crystallizations were mostly discovered at construction joints, inspection wells, and blind ditches, among which 74% of the crystallizations were at construction joints; the main constituent of *in-situ* crystals is calcite calcium carbonate, but the crystal stacking modes and micromorphology varied based on their locations in tunnel. The crystals at the construction joints are cubic with grains stacked in average-sized layers; those at the inspection wells are elliptic with larger grains loosely distributed; those at the blind ditches are acicular with cluster grains but greatly varied sizes. This paper proposes optimizations towards water stop structure and inspection wells in drainage ditch based on positions that are prone to crystallizations, providing a novel idea for solving the crystallization problem in the tunnel drainage system from the perspective of prevention and detection.

*Keywords:* Tunnel engineering; Calcium carbonate crystallization; Drainage system; Water stop; Inspection well

## 1. Introduction

Over the past few years, China has been expanding its tunnel network at a remarkable pace, with over 1,100 km of new tunnels added each year [1]. During the construction and operation of these tunnels, around 80% of the blockage in drainage systems came from crystallization. This blockage may result in increased water pressure behind the lining, which may cause cracking, deformation [2–4], and even water leakage. An increasing number of experts and scholars are conducting research on how to prevent crystalline blockages in tunnel drainage systems.

According to Dietzel et al. [5,6] and Rinder et al. [7], the main reason of crystallization in tunnel drainage pipes is the dissolution of concrete minerals when groundwater ran past the initial shotcrete, flew into the drainpipe and precipitate. Qian et al. [8] conducted field surveys and indoor experiments in tunnels in southern China, and found that the amount of crystallization in drainage pipes is closely related to the water flow velocity and the purity of the $CaCO_3$

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crystals. Xiang et al. [9] conducted indoor experiments on the crystallization of tunnel drainage pipes in alkaline environment and found that the pH value has a significant impact on the amount of crystallization, with a positive correlation between the two under the same conditions.

Both domestic and foreign research have made significant progress in preventing crystalline blockage in tunnel drainage systems. Ye et al. [10] and Tian et al. [11] established a tunnel model and conducted indoor experiments considering factors such as concrete proportioning and design of tunnel drainage system, providing new ideas for preventing crystalline blockage in tunnel drainage systems. Liu et al. [12,15,16] proposed a new flocking drainage pipe under the principle of peristalsis and conducted a large number of indoor experiments, providing ideas and options for indoor experimental design on crystalline blockages. Jung et al. [13] conducted an experiment of using quantum stick to remove scale, which results showing that the quantum stick had a certain descaling function, providing a new method for descaling.

The prevention of crystalline blockage in tunnel drainage systems has been studied from various perspectives. In the long term, optimizing tunnel structures and drainage system designs during tunnel construction could be an effective solution. Through *on-site* investigations, this paper analyzed the causes and the micromorphology of the crystallizations based on their positions by means of X-ray diffraction (XRD) and scanning electron microscopy (SEM) in multiple operating tunnels. Based on the research findings and analysis, this study provides optimization suggestions on preventing crystallizations in tunnel drainage pipe.

## 2. Locations of crystalline blockage in operational tunnels

### *2.1. Overview of the supported project*

Pingtian tunnel is located in Shendu Water Town, Shixing County. As a deep-lying long tunnel, its stretches 2,825 m to the left line and 2,798 m to the right with a maximum burial depth of 384 m underground. With sandstone and slate composing most of its stratum, the ground water flows past the debris on talus slope and the cracks in the bedrock's weathered zone. During the survey, underground water depth through drilling ranges from 9.1 to 79.7 m.

Since December 2018, its completion, the tunnel has experienced multiple crystalline blockages in its drainage system. To better understand the situation, a pipeline crawling robot was used to inspect the tunnel drainage system, revealing a large amount of crystalline deposition in blind ditches (as shown in Fig. 1a), and a severe obstruction in horizontal drainage pipes (as shown in Fig. 1b), with some sections blocked up to one-fifth of their caliber.

### *2.2. Locations of crystalline blockage*

The research group investigated the crystallization conditions in ten operational tunnels in Renxin Expressway and Yinghuai Expressway, and recorded the locations of the crystalline blockage (as shown in Fig. 2). The study identified a total of 324 crystalline blockages, with 240 at construction joints, 27 at inspection wells, 51 at side blind ditches, and 6 at water-collecting wells.

As shown in Fig. 2, the highest proportion of crystalline blockages in the tunnel occurred at construction joints, accounting for 74% of the total. Blockages at side blind ditches and inspection wells accounted for 16% and 8%, respectively. The above three core locations of crystalline blockage contribute to 98% of the total blockage, making them the high-risk crystallization areas.

*On-site* comparisons revealed that crystallization occurrence varied based on their locations, as shown in Fig. 3. Crystallizations at construction joints were characterized by white or yellow precipitates accompanied by seeping water. The crystals were hard and piled up in flat layers tightly bound to the tunnel lining. Crystallizations at inspection wells and water-collecting wells were characterized by white flocculent precipitates. Those at side blind ditches appeared as regular white viscous crystals on the surface.

### *2.3. Field sampling and analysis of the crystals*

In order to identify the composition and microscopic characteristics of the crystals, samples were collected from the construction joints, inspection wells, and blind ditches in the tunnels surveyed in this study, as shown in Fig. 4. On a macroscopic level, the crystals were predominantly white in color, with some in contact with concrete and appearing greyish.

XRD analysis was performed on the collected samples, and JADE 6 software was used for data retrieval and processing. The results showed a 97% match with calcite and

(a) (b)

Fig. 1. Crystal blockage in tunnel site (a) crystalline blockage in blind ditch and (b) crystalline blockage in horizontal drainage pipe.

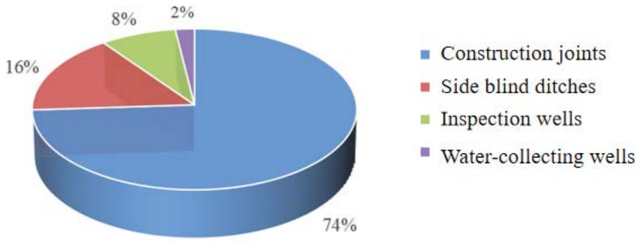



Fig. 2. Locations of crystalline blockage.

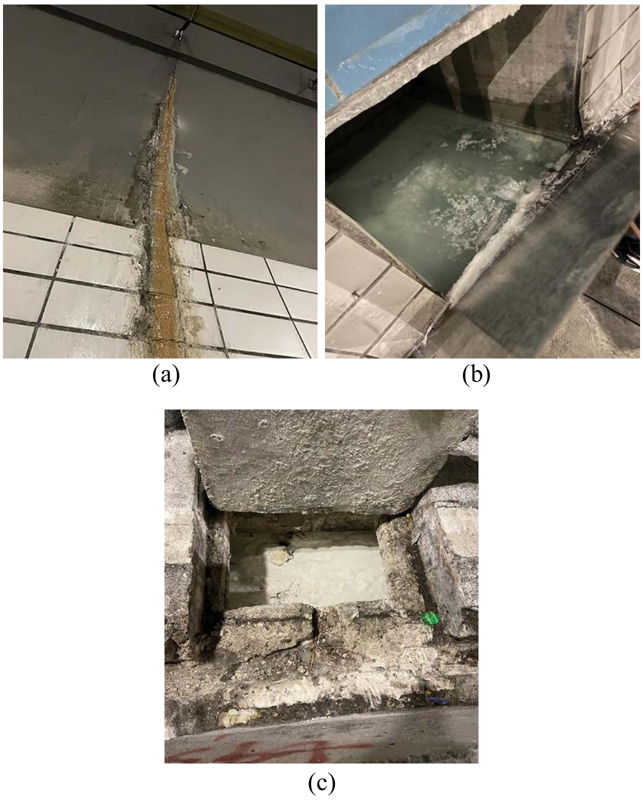



Fig. 3. Crystallization disease found during investigation. (a) Crystallization at a construction joint, (b) crystalline blockage at an inspection well and (c) crystal deposition at a blind ditch.


Fig. 4. Field crystallization sampling (a) crystal sampling from a construction joint, (b) crystal sampling from an inspection well and (c) crystal sampling from a blind ditch.

aragonite. The distribution patterns of the main peaks in the samples were similar to those of calcium carbonate (Fig. 5), indicating that the main component of the crystals on site was calcium carbonate.

The results of the SEM (Fig. 6) show that the deposition pattern of the grains and occurrence of the crystals vary among the locations, though the crystals share the same main composition. At the construction joints, the crystals are arranged regularly with average sizes around 5 to 7 um in diameter and the cubic grains are tightly combined with each other in layers. At the inspection wells, the crystal arrangement is relatively loose with larger sizes up to 22 to 27 um in diameter, and the elliptical grains are spongy in surface. While at the blind ditches, the crystal arrangement is disordered with greatly varied sizes from 2 to 10 um in diameter, and the acicular grains are interlocked in clusters. These indicate that the crystal morphology of tunnel crystallizations is susceptible to their surroundings, and the environments of locations could result to differences in the micro-morphology of crystals, which confirms the conclusion by the study of Feng et al. [14].

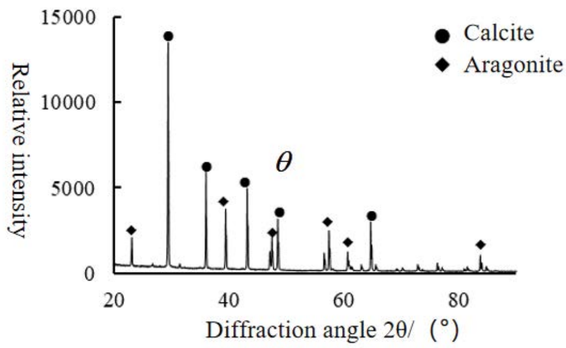
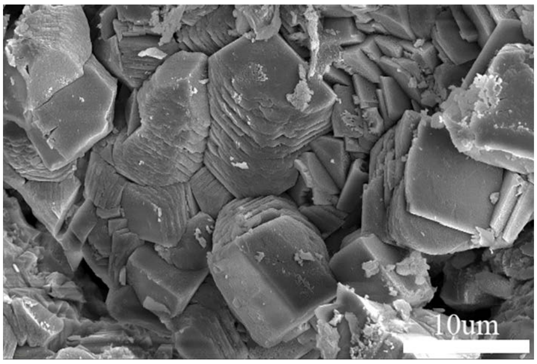



Fig. 5. X-ray diffraction patterns of sample.

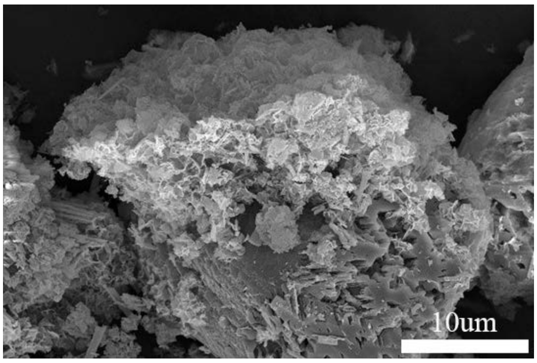
### 2.4. Analysis of investigation results

Based on the findings from the field investigation, it was observed that water leakage through construction joints is the most common form of drainage system damage, occurring over the widest area in high frequency. Water leakage through construction joints is usually accompanied by precipitation of calcium carbonate, which may affect the structural integrity of the lining.

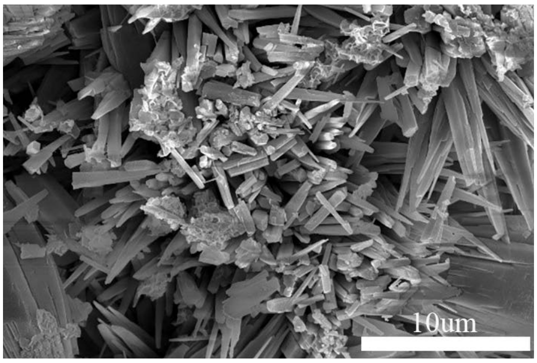
The main reason for water leakage through construction joints is the damage to the water stop. Typically, a buried water stop is used at the construction joints in the tunnel, but it could not be completely fixed due to limitations of its installation method. After the water stop is installed, if the concrete on the side of the water stop is excessively vibrated during compaction, it could lead to a mal-positioning or a damaged water stop, thus affecting its effectiveness. When tunnel drainage pipes are clogged with crystallizations, the whole tunnel drainage system will be influenced.




(a)




(b)




(c)

Fig. 6. (a) Scanning electron microscopy images from the construction joint, (b) inspection well and (c) blind ditch.

The accumulated groundwater behind the lining could not be drained out in time, therefore it could only seep out through the construction joints which are not completely watertight. When groundwater passes through concrete, chemical reactions and crystallizations occur.

Based on the field investigation, it can be inferred that crystalline blockages in the inspection wells and the blind ditches are closely related to those in the drainage pipes. When the drainage pipes are blocked by crystals, groundwater could not be drained off as usual. Then large amount of groundwater containing crystals flows back into the inspection wells and accumulate in the blind ditches, resulting in crystalline blockages. This indicates that many crystalline damages are caused by the blockage of drainage pipes, affecting the smooth operation of the tunnel drainage system. Therefore, to prevent crystalline blockages in the tunnel drainage system, it is necessary to strengthen the anti-crystallization function of the drainage pipes and optimize the function of the construction joints, inspection wells, and blind ditches.

## 3. Optimizing suggestions on preventing crystallization in tunnel crystallized locations

After analyzing the *on-site* engineering data and the locations of the crystallization disease, it can be seen that the disease does not only occur in drainage pipes but also in areas such as construction joints, inspection wells, and blind ditches. Attention needs to be paid on the serial problems of tunnel drainage system caused by crystalline blockages of drainage pipes. Based on the actual investigation, this section provides optimizing suggestions for preventing crystallization in tunnel construction joints, drainage ditch inspection wells, and blind ditches.

### *3.1. Structural optimization of water stop at construction joints in lining*

The necessity of optimizing the structure and the design of water stop is due to its performance defects which lead to crystallization damage in construction joints. The conventional buried water stop needs to be fixed between the tunnel initial support and the lining with end templates, and the inner and outer templates need to be installed, respectively. The process is difficult and inconvenient, and the templates around the water stop are prone to insufficient sealing. During the pouring of the lining concrete, the steel bars installed in the lining could be damaging the end templates of the water stop and causing a loosening water stop. These factors might lead to displacement of the water stop and therefore hinder its water-sealing effect.

#### *3.1.1. Novel anti-crystallization water stop belt*

A novel "π"-shaped anti-crystallization water stop belt in construction joints of lining (referred to as the novel water stop belt) could be introduced, which incorporates the benefits of buried-type water stop belts commonly used in China.

The novel water stop belt consists of geotextile, a groove, water stop belt ribs, water stop belt wings, a fleece layer, and a semicircular hose, as shown in Figs. 7 and 8. The groove is the main part of the water stop belt, which serves to fix the semicircular hose and connect other structures. The concave part at the bottom of the groove allows the water stop belt to be better stressed during installation. The water stop belt ribs are set on top of the water stop belt wings to increase the overall structure's resistance to pull-out force and prevent the water stop belt from deflecting due to concrete vibration during construction. The geotextile is placed at the top to prevent impurity substances such as mud and sand from entering the semicircular hose and damaging the fleece layer, and therefore affecting the anti-crystallization function of the water stop belt and filtering groundwater that flows into the construction joint.

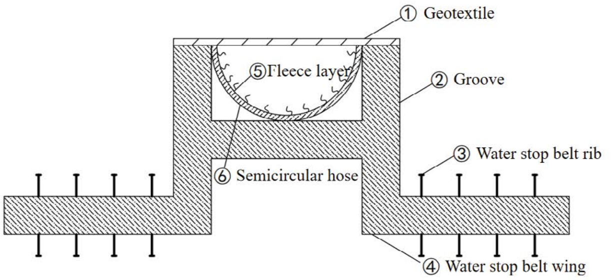



Fig. 7. Schematic diagram of the novel water stop belt structure.

Fig. 8. Schematic diagram of the novel water stop belt structure.

Apart from providing the same sealing performance as ordinary water stop belts, the novel water stop belt also boasts a built-in drainage function. The semicircular hose placed within the water stop belt redirects the groundwater that seeps into the construction joint from behind the lining towards the longitudinal drainage pipe, thus substantially minimizing the water pressure on the water stop belt. In addition, the new water stop belt serves as an anti-crystallization and blockage-preventing device due to setting of the fleece layer.

Compared to traditional buried water stop belts, the novel water stop belt comes with several advantages.

(1) Firstly, it is economically beneficial: it has a built-in drainage system that reduces the need for installing additional pipes and minimizes water leakage and crystallization during the operation stage, thereby lowering the overall construction and maintenance costs.
(2) Secondly, the end templates used during the installation process are reusable, and there is no need to disconnect them or use rebar clamps as auxiliary tools, making it a zero-loss installation process.
(3) Lastly, the process of installing buried water stop belts is rather complex: it requires placing the water stop belts between the linings using end templates on both sides and fastening them with reinforcement and clamps. In contrast, the novel water stop belt only needs to be positioned by inserting the end template into the bottom of the groove, which greatly speeds up the installation process.

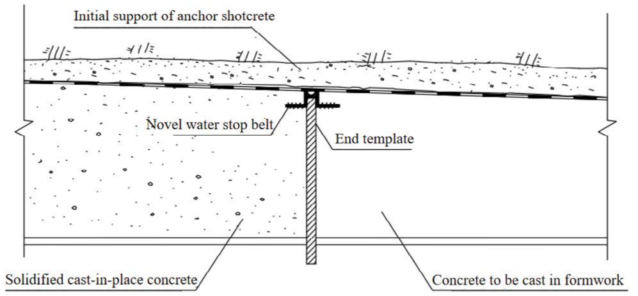



Fig. 9. Schematic diagram of inspection well location optimization.

*3.1.2. Installation steps of the novel water stop belt*

The installation of the novel water stop belt is quite convenient. The end template needs to be simply mounted on the concrete formwork of the lining cart and pressed onto the recessed slot of the belt, as shown in Fig. 9. The specific steps are as follows:

- Temporary fixing of the water stop belt: insert the end template into the recessed slot of the water stop belt and temporarily fix it. During this process, it is necessary to ensure that the belt is flush with the outer contour of the tunnel, and the degree of adhesion of the belt can be adjusted by controlling the number of end templates inserted and the fixing strength.
- Connecting the water stop belt to the tunnel drainage system: after confirming the actual length of the water stop belt, cut off the excess part of the belt, and then connect the internal drainage pipe of the water stop belt to the longitudinal drainage pipe. Since the pipe inside the water stop belt is semicircular hose, which cannot be connected directly to the longitudinal drainage pipe, a straight-through pipe with the same diameter as the semi-circular hose can be vertically set at the corresponding position of the longitudinal drainage pipe, and the hose can be inserted directly into the straight-through pipe.
- Fixing the water stop belt: use the end template to press the belt from bottom to top to fix it, and the installation is complete.

*3.2. Optimization of locations of drainage ditch inspection wells*

Inspection wells serve the purpose of observing and cleaning the blind ditches, providing a visual representation of their blockage status. Keeping these wells unobstructed and maintaining their cleanliness could in part prevent their blockages. Typically, the cleanup of the inspection wells is done by maintenance personnel dispatched by the responsible agency. To ensure uninterrupted traffic flow through the tunnel, this method still suffers from problems such as insufficient prevention measures, limited range of cleaning and observation, high labor costs, and potential safety hazards to the workers involved. To address these issues, inspection wells could be positioned at pedestrian tunnels, where transverse blind ditches could be added and connected perpendicular to tunnel side blind ditches, as

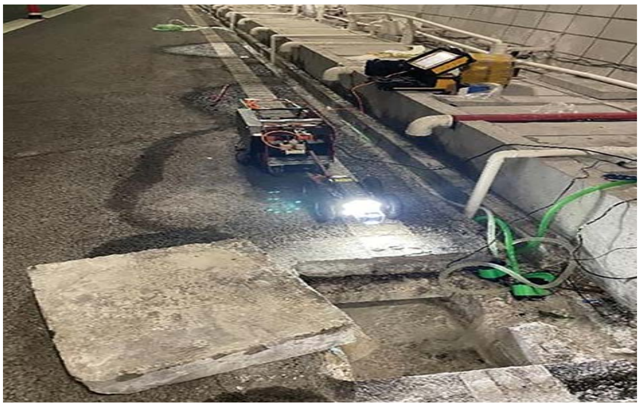


Fig. 10. Tunnel detection by pipeline crawling robot.

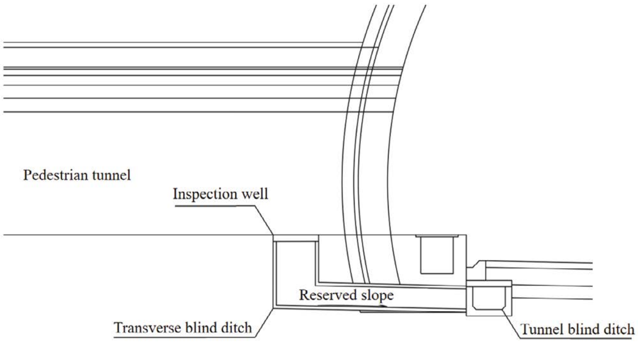



Fig. 11. Inspection well location optimization diagram.

shown in Fig. 10. The blind ditches could then be periodically inspected with pipe-crawling robots. During the tunnel operational period, the inspection wells could be opened on a regular basis for robot inspections to promptly detect and locate any accumulated crystallizations that may cause blockages. This approach requires much less human labor and ensures the safety of the maintenance workers while avoiding disruptions to tunnel traffic [15,16].

During construction, the arrangement of transverse blind ditches should be located based on the actual conditions of the projects. Generally, the ditch is set every 450 m along the pedestrian tunnel. The crawling distance of the pipeline robot used in this inspection is around 300–400 m. In order to make sure the blind ditches of the tunnel are fully covered with inspection, the location of the inspection well could be set at the entrance of the pedestrian tunnel, and the distance between the axis of the inspection well and the blind ditch should be around 3 m. To ensure sufficient crawling space for the robot, the width of the transverse blind ditch should align with that of the tunnel side blind ditch while a slope should be reserved to ensure proper drainage (Fig. 11).

## 4. Conclusion

This paper analyzed the composition and micromorphology of the *on-site* crystal samples, located positions that are prone to crystallization inside the tunnel, and proposed suggestions for preventing crystallization disease based on the *on-site* data and actual investigation of the tunnel in operation period, the main conclusions are as follows:

- The construction joints, inspection wells, and blind ditches are high-risk areas for crystallization disease, with construction joints accounting for 74% of the observed disease. The occurrence of the crystallizations in these areas are different: water leakage with crystal precipitation in the construction joints, overflowing of water with crystal precipitation in the inspection wells, and crystal accumulation and blockage in the side blind ditches.
- The main component of the crystals from overall the tunnel is calcite calcium carbonate but with varied micromorphology and stacking mode. At the construction joints, the crystals are cubic in layers with regular sizes. At the inspection wells, the crystals are elliptical and loosely stacked with larger sizes. In the blind ditches, the crystals are acicular and stacked in cluster with greatly variable sizes.
- Suggestions are proposed to prevent crystallization damage in the areas of construction joints, inspection wells, and blind ditches. A novel "π"-shaped anti-crystallization water stop belt in construction joints of lining has been designed to prevent crystallizations while optimizing the installation of the water stop belt. Additionally, inspection wells could be installed at the entrance of pedestrian tunnels and connected to the tunnel side blind ditch, enabling pipeline crawling robots for detecting the condition in the blind ditches.

Further study could be carried out on the application of anti-crystallization optimizations in drainage system in newly constructed tunnels to provide more comprehensive and reliable suggestions.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