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STUDY ON WATER LEAKAGE DETECTION AND TREATMENT IN METRO STATION STRUCTURES

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Abstract

Introduction: Considering the condition of water leakage at metro stations and the availability of various leakage detection methods, studying combination detection methods suitable for various working conditions can serve as the basis for leakage treatment. **Purpose of the study:** We aimed to use a number of leakage detection methods that can complement and verify each other in terms of accuracy and depth of detection, improve the identification of defects, and ensure precise grouting. **Methods:** In the course of the study, model tests and field application of detection methods were used. **Results:** Using an infrared detector and a water leakage detection instrument, it is possible to identify leakage points on the surface of both the non-decorative layer and the wet-sticking decorative layer more accurately. By combining a ground penetrating radar and an ultrasonic cross-section scanner, it is possible to better identify internal structural defects within both the non-decorative layer and the wet-sticking decorative layer. If the decorative layer is not dismantled, an air-coupled radar based on an industrial endoscope and a specially developed camera system can effectively detect the leakage path in concrete as well as surface leakage points.

Keywords: subway, station design, water leakage, comprehensive inspection, grouting repair.

Introduction

The increased groundwater level, combined with more precipitation during flood and rainy seasons, and the issue of waterproof failure in older metro structures lead to more severe cases of water leakage. According to the statistical analysis of data ion water leakage at 19 underground line structures in Beijing in recent five years, the structural leakage shows an upward trend. The number has grown from 2,226 in 2017 to 3,505 in 2021, which is a 57.5% increase. The leakage point statistics are shown in Fig. 1.

The existing water leakage remedial effect is generally poor. The main reason is that the location of the water leakage disease in the concrete structure is not clear before remediation. Blind remediation, which only relies on superficial symptoms, cannot achieve the purpose of treating both the symptoms and root causes of water leakage. As a result, this leads to the recurring issues of "treating water leakage wherever it occurs" and "treating water leakage only for it to occur again after the remediation". This not only requires a significant amount of manpower and resources, but also does not ensure the desired remedial effect. Due to the presence of a decorative floor and the impact of train operation, it becomes challenging to determine the exact location of the leakage point at a metro station. Through systematic investigation and analysis of water leakage defects in existing stations, three specific defects were identified as research objects: groundwater return, water accumulation in straight ladder wells, and side wall leakage. Method for rapid detection of water leakage defects were studied with regard to three complex concrete structures in order to quickly locate water leakage and assess the internal condition of the concrete, thus elucidating the causes of water leakage defects. Based on the main structure and zoning of metro stations, and taking into account functional zoning and decorative layers, five different conditions related to water leakage were identified in three types of concrete structures: leakage from the side walls of dry-hanging decorative layers, leakage from the side walls of non-decorative layers, groundwater return in wet-sticking decorative layers, groundwater return in non-decorative layers, and water accumulation in straight ladder wells.

Gong and Guo (2021) discussed the types and causes of water leakage, the methods and principles of detecting leakage during operation, the concepts and technical measures for preventing water leakage during design and construction, and the meaning and methods of water leakage remediation during construction and operation. Asakura and Kojima (2003) introduced the maintenance methods for tunnels in Japan during operation. Sandrone and Labiouse (2011) addressed the analysis and identification of defects related to highway tunnels in Switzerland. Shi and Li (2015) studied the mechanisms of tunnel defects and

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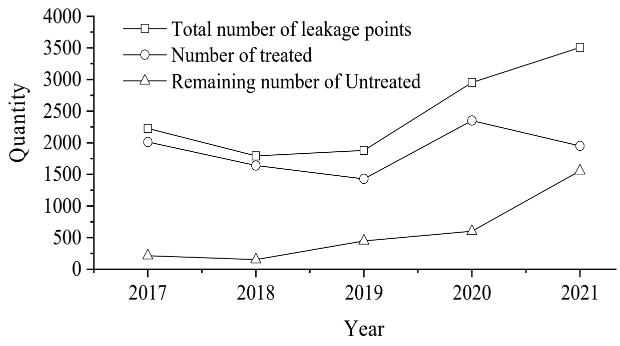


Fig. 1. Statistical chart of structural leakage data

structural deterioration in soft soils. Montero et al. (2015) introduced the use of a robot for tunnel detection. Clark et al. (2003), Ma et al. (2022), and Yu et al. (2016) studied the application of infrared thermography in tunnel leakage detection. Musolino et al. (2007) investigated the feasibility of a diagnostic method for non-destructive testing (NDT) of concrete structures based on ultrasonic wave propagation. Jiang et al. (2020) discussed the application of the impact elastic wave method in detecting areas of low density and voids in concrete. Cheng et al. (2021), Feng et al. (2011), Han et al. (2012), Kashani et al. (2015), and Liu et al. (2009) analyzed the effects of GPR application in detecting tunnel leakage defects. A new method was proposed for underground water leakage detection in tunnels using corrected intensity data and a 3D point cloud of a terrestrial laser scanning (TLS) sensor (Xu et al., 2018). Liu et al. (2012) developed a set of digital image processing algorithms to detect tunnel lining water leakage defects, which include denoising, sharpening, segmentation, and correction. Lam (2006) explained the process of choosing an appropriate laser scanner, calibrating it, acquiring survey data in the field, and using computational algorithms for image registration, fusion, and error analysis. These advancements enable the effective use of point clouds in evaluating the geometric tolerances of tunnel structures during as-built survey.

However, most of the existing detection studies are aimed at concrete structure defects rather than water leakage defects. Most of the existing studies focus on one detection method, and there is no comprehensive application of various detection methods to enhance detection accuracy and efficiency. The current specification (Chinese State Standard, 2010, 2022) for detection methods and conditions for detection objects is somewhat limited, which is not suitable for complex station conditions. There are very few specific or inherent specifications for detecting structural leakage. Therefore, it is necessary to study a detection method for identifying leakage points and leakage paths in metro stations. This will help determine the causes of the leaks, pinpoint the exact location of the problem, and facilitate accurate grouting.

Research on Combined Detection Technology

After conducting an investigation, the characteristics and advantages of various concrete leakage disease detection equipment and detection methods are analyzed. In order to accurately detect internal defects in concrete, it is necessary to comprehensively utilize the advantages of various equipment. This allows for the combined detection of different depths and different types of defects. Ultimately, a solution can be formed for accurately locating leakage points in concrete structures and detecting various internal disease forms.

Based on the conditions of water leakage in metro stations and the applicability of various detection methods, appropriate detection methods for different conditions are proposed. The corresponding detection equipment is selected according to the detection methods, as shown in Table 1.

The proposed combined detection method utilizes video imaging technology to detect water leakage points on the back surface of the dry-hanging decorative layer. It specifically aims to improve the video imaging and image mosaic technology for blocks and partitions. In cases where the surface leakage cannot be captured in a single panoramic shot, the software can stitch and merge multiple images taken in blocks to create a complete detection area image. This allows for accurate positioning of leakage points and identification of the type of disease. With the combination of the infrared thermal imaging technology and leakage detection technology, it is possible to detect surface leakage points of side wall seepage, groundwater return, and elevator shaft leakage without a decorative layer. In terms of detecting internal concrete disease leakage paths, detection accuracy and efficiency are improved by utilizing the ultrasonic cross-section scanning technology and radar detection technology, which enable combined detection, data complementarity, and interactive verification. Additionally, the grid detection technology is employed to achieve a 3D representation of the morphology of internal concrete defects.

Model Test Analysis

In order to simulate the application effect of the detection method and verify the accuracy of the detection results for various types of defects, a concrete block with 0.5 m × 0.5 m × 1.5 m dimensions was made. This block contained an empty bottle, a bottle with water, an earth bag, a stone bag, and linoleum paper to simulate a cavity, water content, slag inclusion, porosity, and cracks, respectively. After the curing of concrete specimens under standard conditions was completed, the detection method was adopted to locate simulated disease. The simulated disease location and concrete specimens are shown in Fig. 2. The internal defects of concrete specimens were detected using

Table 1. **Detection methods under different conditions**

No.	Conditions	Detection method
1	Groundwater return without a decorative floor	Combined detection of surface leakage points: infrared thermal imaging method and water leakage detection method. Combined detection of structural internal defects: GPR method, ultrasonic 3D scanning method, and concrete perspective instrument method.
2	Groundwater return in the wet-sticking decorative layer	Combined detection of surface leakage points: infrared thermal imaging method and water leakage detection method. Combined detection of structural internal defects: GPR method, ultrasonic 3D scanning method, and concrete perspective instrument method.
3	Side wall leakage without a decorative layer	Combined detection of surface leakage points: infrared thermal imaging method and water leakage detection method. Combined detection of structural internal defects: GPR method, ultrasonic 3D scanning method, and concrete perspective instrument method.
4	Side wall leakage in the dry-hanging decorative layer	Combined detection of surface leakage points: endoscope, specially developed camera system; Combined detection of structural internal defects: air-coupled ground penetrating radar.
5	Water accumulation in straight ladder wells	Combined detection of surface leakage points: infrared thermal imaging method and water leakage detection method. Combined detection of structural internal defects: GPR method, ultrasonic 3D scanning method, and concrete perspective instrument method.

a ground penetrating radar and an ultrasonic 3D scanner. Based on the model size, five radar survey lines were arranged, with two on the front side, two on the back side, and one on the top. The survey line arrangement is shown in Fig. 3.

Since a 900 MHz radar antenna was used for detection, the theoretical resolution was 2.8 cm. However, due to the influence of instruments and the detection environment, the actual resolution was about 4 cm. Therefore, the radar could not detect a cavity with a diameter of 1 cm. Due to the pre-existing water storage in the borehole, the radar wave was sensitive to water. As a result, there was a prominent reflection point on the survey line result map that corresponded to the borehole position. It is inferred that this reflection point indicates a leakage point in the borehole. The detection results for the survey lines are shown in Fig. 4.

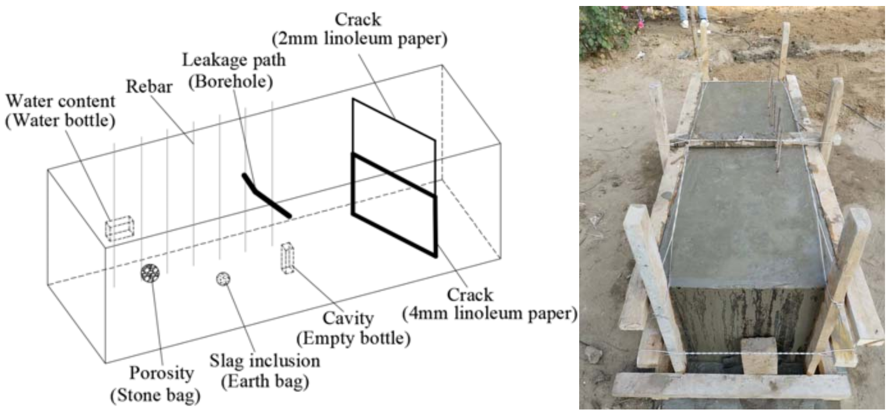


Fig. 2. Schematic diagram of disease location and concrete specimen

Fig. 3. Survey line arrangement of defects location on concrete specimen

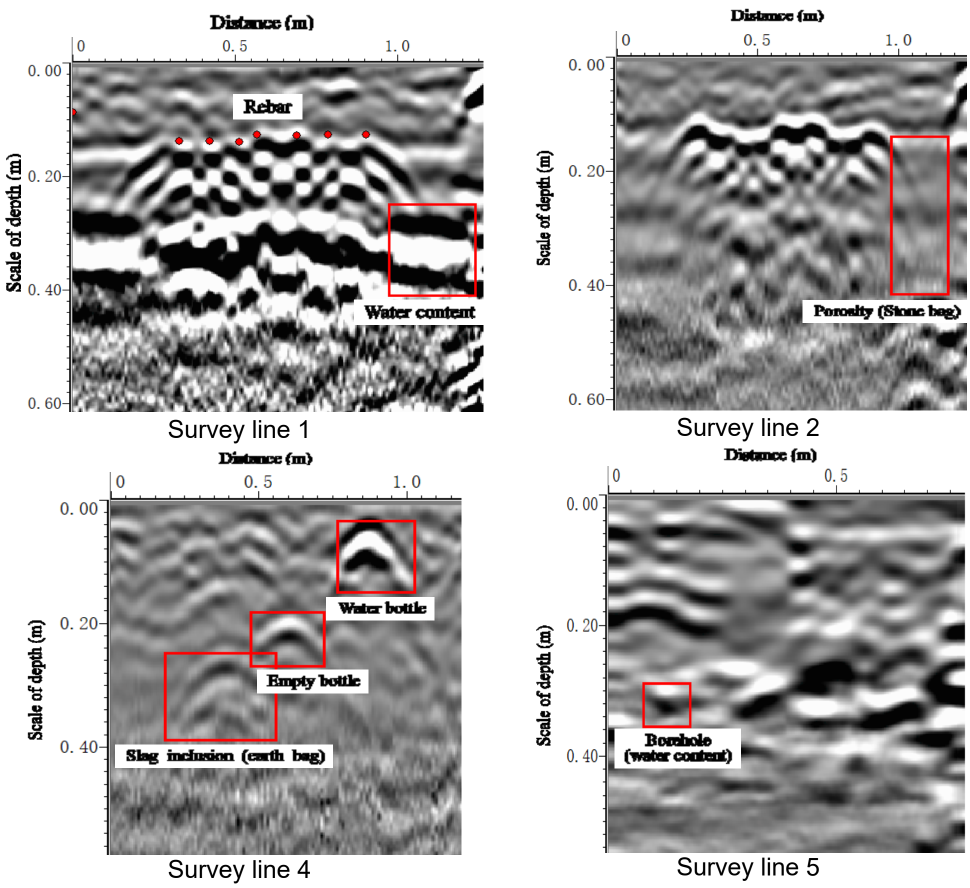


Fig. 4. Map with the radar detection results for each survey line

The ultrasonic 3D scanner was used to detect the shape of a concrete specimen, and the results of the detection in different display modes can be seen in Fig. 5. Due to its high precision, the ultrasonic 3D scanner can identify more abnormal areas and encounter interference if the concrete is unevenly poured. When the size of the disease is small, other methods are needed to verify and enhance accuracy.

Through model tests, the standard GPR waveform diagram of the disease was summarized, and the reliability of the detection method was verified. This provides a reference for applications in engineering detection.

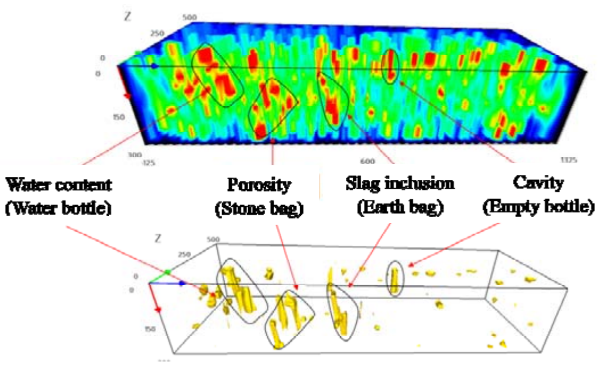


Fig. 5. Map with the detection results from the ultrasonic 3D scanner

Analysis of Detection Method Engineering Application

According to the five conditions of the metro station, namely: groundwater return without a decorative layer, groundwater return with a wet-sticking decorative layer, side wall leakage without a decorative layer, side wall water accumulation with a dry-hanging decorative layer and straight ladder wells, corresponding test points were selected for combined detection.

1. Groundwater return without a decorative floor

According to the detection method proposed in Table 1, an infrared detector and a water leakage detection instrument were used to detect the leakage point under the condition of groundwater return without a decorative layer. A ground penetrating radar (900 MHz and 400 MHz), an ultrasonic 3D scanner, and a concrete steel bar perspective instrument were used to detect internal defects in the concrete. The detection lines are arranged in a grid of 30cm x 30cm (Fig. 6), the leakage point detection results are shown in Fig. 7, and the results of internal structural defects detection are shown in Fig. 8.

As can be seen from Fig. 7, the blue area in the infrared thermal image represents the area with low temperature abnormalities. The value measured at the same position by the water leakage detection instrument can be inferred as the point of water leakage.

As can be seen from Fig. 8, the ultrasonic 3D scanning map, along with the infrared thermal image and the water leakage detection instrument, shows that there is a disease in the concrete of the bottom slab at this location. It was verified through drilling that this position is indeed a point of leakage.

After a comprehensive inspection, both the infrared thermal imager and the leakage water detection instrument detected abnormalities at the same location. This confirms that there is a surface leakage point in that area. Furthermore, the ultrasonic 3D scanner, which has an accuracy of 1 cm, was utilized to identify concrete quality issues

Fig. 6. Layout drawing of the groundwater return condition detection line without a decorative floor

Fig. 7. Results for the groundwater return condition detection line without a decorative floor for leakage point detection

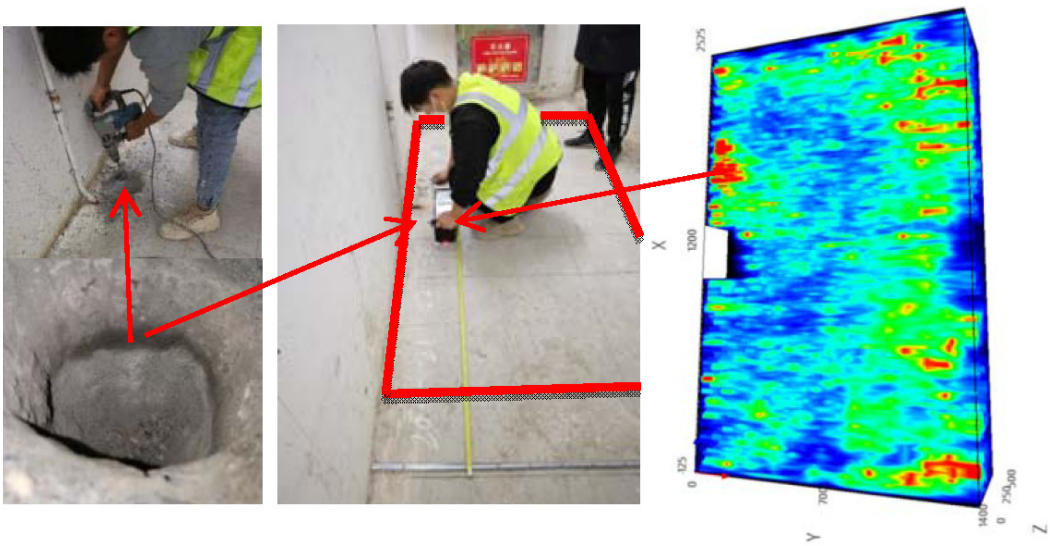


Fig. 8. Results of the detection of internal defects in the structure for the groundwater return condition detection line without a decorative floor

at the same point. The results from the surface detection were also supported by the findings from the ultrasonic scanner. The ground penetrating radar did not detect any abnormality here because the size of the disease is small. The ground-penetrating radar can distinguish defects of 3 cm minimum.

2. Groundwater return in the wet-sticking decorative layer

The infrared thermal imager and water leakage detection instrument were used to detect the leakage point for the groundwater return condition in the wet-sticking decorative layer. Additionally, the ground penetrating radar (900 MHz and 400 MHz), ultrasonic 3D scanner, and concrete steel bar perspective instrument were used to detect the leakage path.

The leakage point detection results are shown in Fig. 9, and the results of internal structural defects detection are shown in Fig. 10.

As can be seen from Fig. 9, the red area in the infrared thermal image represents the area with high temperature abnormalities. The value measured at the same position by the water leakage detection instrument can be inferred as the point of water leakage. As can be seen from Fig. 10, the ultrasonic 3D scanning map, at the same position

Fig. 9. Leakage point detection results for groundwater return in the wet-sticking decorative layer

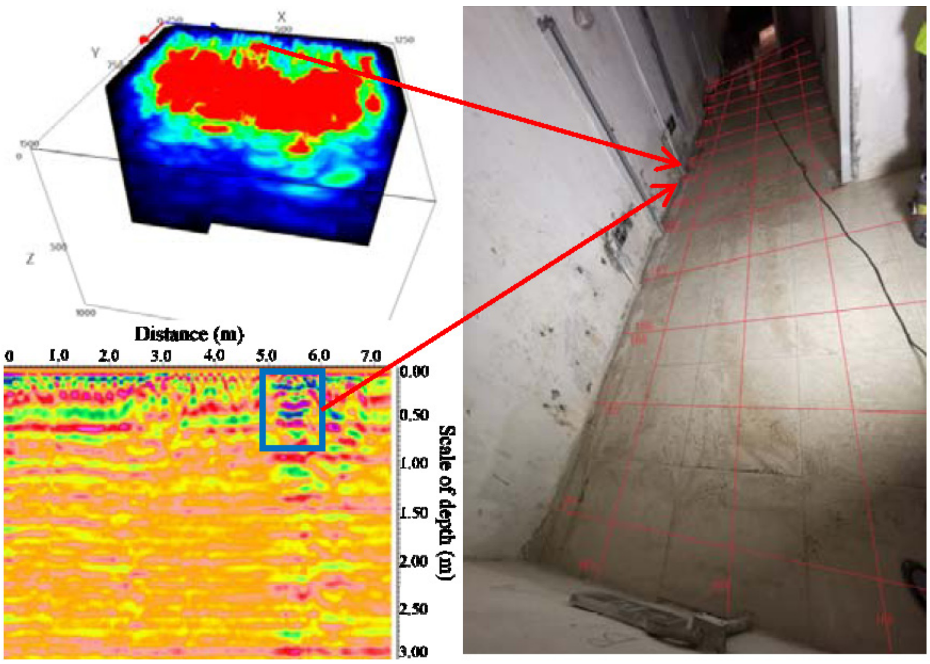


Fig. 10. Results of internal structural defects detection for groundwater return in the wet-sticking decorative layer

as the infrared thermal image and the water leakage detection instrument, shows that there are defects in the bottom slab's concrete. These defects were also detected by the GPR.

After conducting the combined detection, both the infrared thermal imager and the water leakage detection instrument detected abnormalities at the same location, indicating that this area is the source of surface leakage. Additionally, the ultrasonic 3D scanner, with a precision of 1 cm, was used to identify concrete quality issues at the same spot, confirming the results of the surface detection. Furthermore, the ground penetrating radar also identified an abnormality in this area, with the size of the disease being approximately 1 m in length.

3. Side wall leakage without a decorative layer

The infrared thermal imager and water leakage detection instrument were used to detect the leakage point in the side wall without a decorative layer. Additionally, the ground penetrating radar (900 MHz and 400 MHz), ultrasonic 3D scanner, and concrete steel bar perspective instrument were used to detect the leakage path. The diagram in Fig. 11 shows the implementation of combined field detection at test points.

The results of identifying leakage points and internal structural defects are displayed in Fig. 12. As shown in Fig. 12, the blue area in the infrared thermal image represents the area with low temperature abnormalities. The water leakage detection instrument reveals a high reading in this area, indicating that it may be the point of surface leakage. Moreover, the blue abnormality area in the ground penetrating radar map denotes a crack, which is consistent with the actual situation on site. The position highlighted by the black box in the ultrasonic 3D scanning image coincides with the location of the surface leakage point detected by the infrared thermal imager and water leakage detection instrument.

4. Side wall leakage in the dry-hanging decorative layer

The back side of the decorative layer can only be detected using an industrial endoscope. However, the flexible measuring line of the industrial endoscope cannot effectively detect behind the top plate and the long-distance side wall. Moreover, the flexible measuring line cannot accurately pinpoint the source of leakage. The invention includes a device and a method for identifying and locating leakage points behind the decorative layer of metro stations. The detection method can not only determine the leakage point behind the decorative layer but also grasp the surrounding environment and coordinate the positioning of the leakage point behind the decorative layer. The equipment is not subjected to the height of the roof decorative layer, as shown in Fig. 13.

The surface leakage point of the side wall with the dry-hanging decorative layer was detected using an industrial endoscope and a specially developed camera system. The leakage path was identified using an air-coupled ground penetrating radar (400 MHz). The diagram in Fig. 14 shows the implementation of combined field detection at test points.

The results of identifying leakage points and internal structural defects are displayed in Fig. 15.

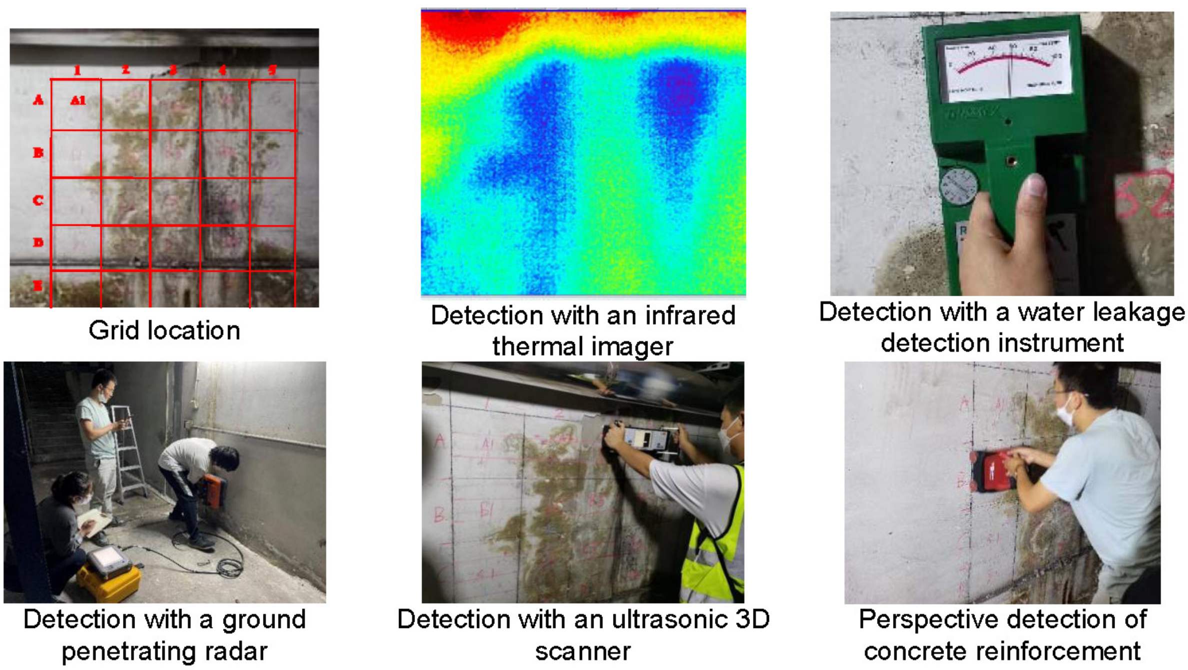


Fig.11. Diagram for implementing combined detection of side wall leakage without a decorative layer

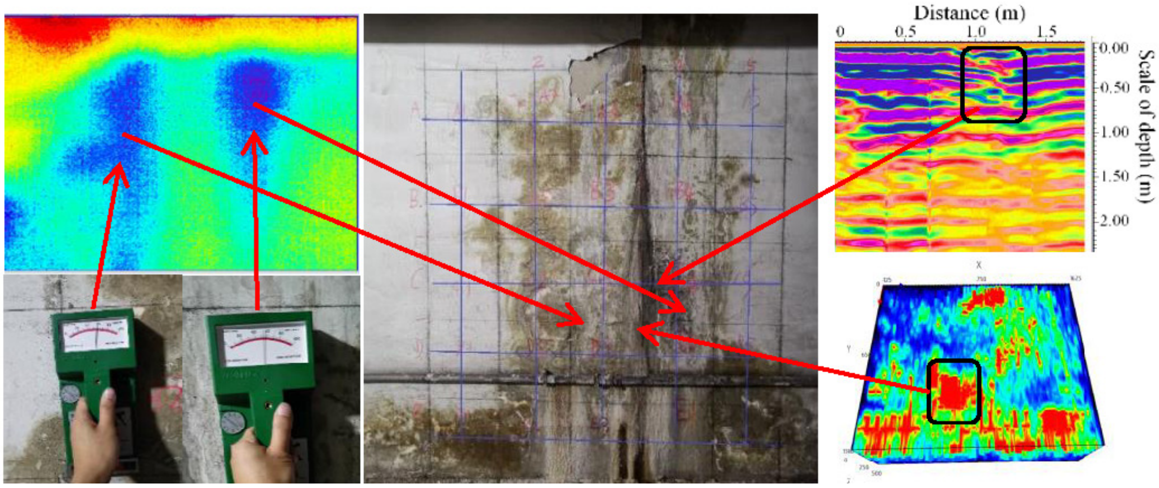


Fig. 12. Results of combined detection of side wall leakage without a decorative layer

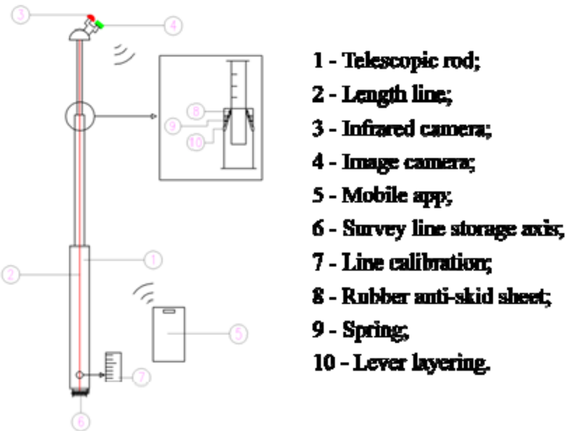


Fig. 13. Schematic diagram of a combined detection device for identifying leakage points behind the decorative layer

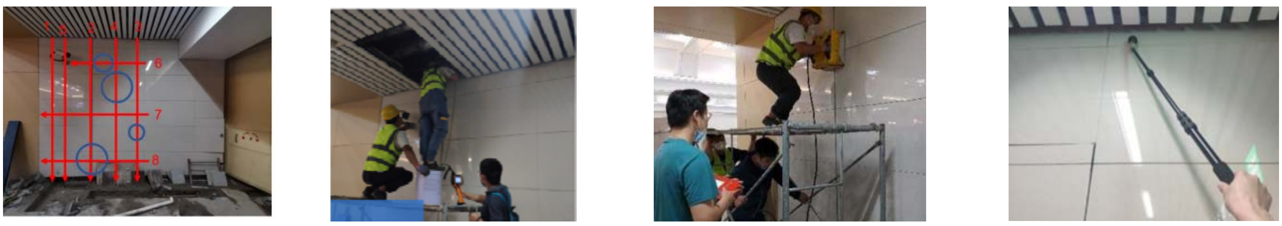
As can be seen from Fig. 15, the combination of an industrial endoscope, a specially developed camera system, and a ground penetrating radar can be used to detect the leakage condition of the side wall with the dry-hanging decorative layer. It can determine the location of the leakage point, reduce the need for demolition of the decorative layer, and improve remedial efficiency. In the figure, the red numbers represent the location of the survey line, and the yellow numbers represent the location of the ceramic tile in the decorative layer.

5. Water accumulation in straight ladder wells

The infrared thermal imager and water leakage detection instrument were used to detect the surface leakage points in straight ladder wells under water accumulation conditions. Additionally, the ground penetrating radar (900 MHz and 400 MHz), ultrasonic 3D scanner, and concrete steel bar perspective instrument were used to detect the leakage path. The combined detection results are shown in Fig. 16.

As shown in Fig. 16, due to the recent removal of the accumulated water, the temperature of the bottom plate is fairly even, and the infrared thermal imager cannot detect any areas with abnormal temperatures. Although the accumulated water was removed, the amount of water within 10 cm of the surface layer can still be detected using the water leakage detection instrument. The ground penetrating radar and ultrasonic 3D scanner can essentially identify abnormalities at the same location, which can be basically classified as structural defects.

When the detection method was used for on-site detection, it was found that the infrared thermal imager and water leakage detection instrument were affected by the detection environment and did not function effectively under all conditions. When the



Grid location | Inspection with an industrial endoscope | Detection with a ground penetrating radar | Detection with a specially developed camera system

Fig. 14. Diagram for implementing combined detection of side wall leakage in the dry-hanging decorative layer

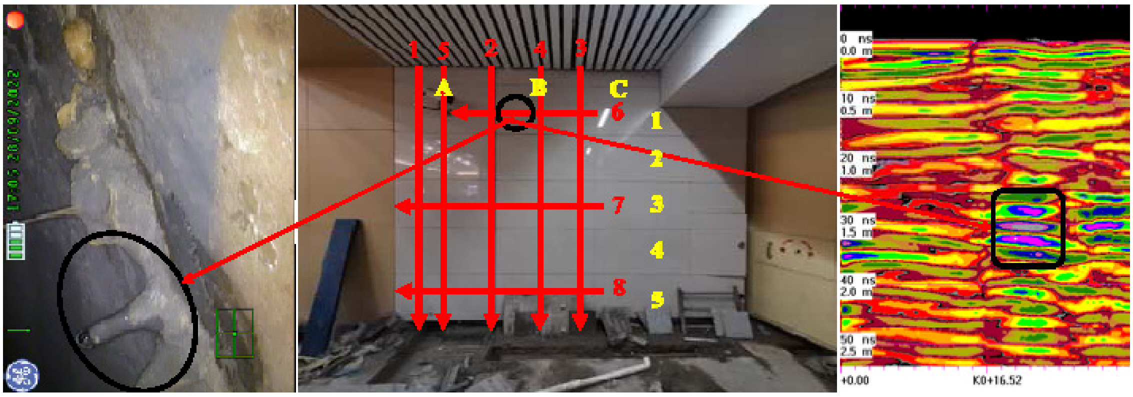


Fig. 15. Results of combined detection of side wall leakage with the dry-hanging decorative layer

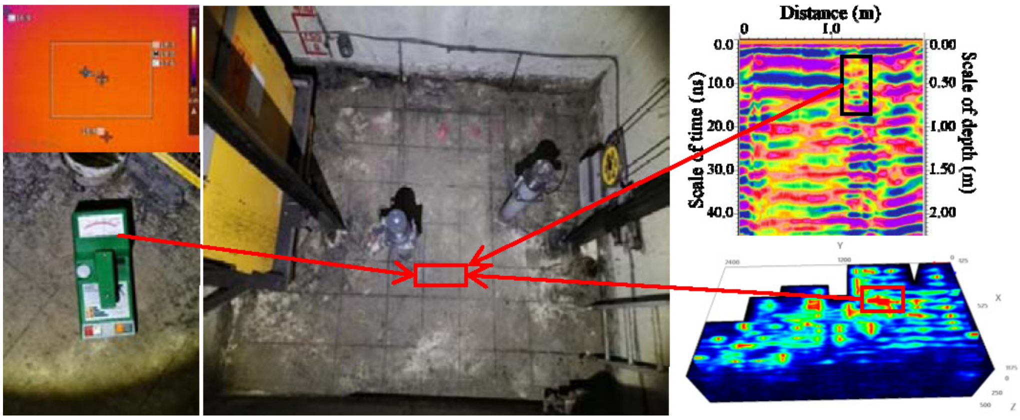


Fig. 16. Combined detection results for water accumulation in the straight ladder wells

concrete defects are small, the detection by GPR and ultrasonic 3D scanning methods is not obvious. However, the detection effect of an infrared thermal imager and a water leakage detection instrument on shallow water enrichment can be used as an important reference. The ground penetrating radar has a high detection efficiency and is suitable for large-scale detection. The ultrasonic 3D scanner has a higher detection accuracy than the ground penetrating radar, but its detection efficiency is low, making it suitable for small-scale detection.

According to the analysis of the combined detection results, it can be seen that:

(1) With the combined detection technology of "infrared detector + water leakage detection instrument", a more accurate preliminary identification of leakage points on the surface of the non-decorative and wet-sticking decorative layers can be achieved.

(2) With the combined detection technology of "GPR + ultrasonic section scanner", the internal defects of the non-decorative layer and wet-sticking decorative layer can be detected more effectively.

(3) Under the condition of not removing the decorative layer, the detection of leakage points in the side wall with the dry-hanging decorative layer mainly depends on the industrial endoscope and specially developed camera system. The leakage path in the concrete can be effectively detected using the air-coupled radar.

Grouting Remediation and Effect Evaluation

Based on the combined detection results for each test point, grouting remediation is carried out at the disease location related to the test point. After grouting remediation, the evaluation of grouting effect mainly includes the following: 1. whether there is still water leakage; 2. geophysical prospecting determines if the leakage path of defects (porosity, cavity, slag inclusion, etc.) is tightly sealed; 3. check the compactness of the grouting through drilling and coring. This paper only offers the grouting remediation solution for groundwater return condition with regard to the wet-sticking decorative layer. Based on the combined detection results, acrylate and modified epoxy resin grouting is performed on the leakage points on the bottom plate surface of the evacuation passageway and in areas with concrete quality issues (leakage paths). The grouting remediation site is shown in Fig. 17, whereas the apparent effect after remediation can be seen in Fig. 18. The ground penetrating radar detection result is displayed in Fig. 19. To ensure more accurate verification of the

Fig. 17. On-site grouting remediation for groundwater return condition with regard to the wet-sticking decorative layer

grouting effect, drilling and coring were performed in the B10 area (Fig. 20).

Conclusions

During the field implementation process, leakage points and types of leakage defects were initially investigated using engineering experience. Afterwards, the combined detection was conducted to accurately locate and determine the types of leakage defects. Based on the model tests and field tests, the following conclusions were drawn:

(1) At the initial stage of leakage, there was a significant temperature difference (greater than 0.08°C) between the leaking water and the surrounding environment. The infrared thermal imaging method proved to be effective in locating the points of leakage.

(2) The water leakage detection instrument can detect the water content in a depth of 0 to 10 cm. It is sensitive to the area with water content, but this method requires that the detection surface be flat and free from any water accumulation.

(3) The resolution of the ground penetrating radar is less than 3 cm, and the detection depth is 3 m, while the resolution of the ultrasonic 3D scanner is 1 cm, and the detection depth is 0.5 m. The ground penetrating radar and ultrasonic 3D scanner can verify each other while detecting internal defects in concrete, thereby improving the rate and accuracy of disease recognition.

(4) When the concrete defects are small or greatly affected by the environment, the detection using the ground penetrating radar and ultrasonic 3D scanner. is not obvious. In such cases, the detection of water content in the shallow layer using the infrared thermal imager and water leakage detection instrument can

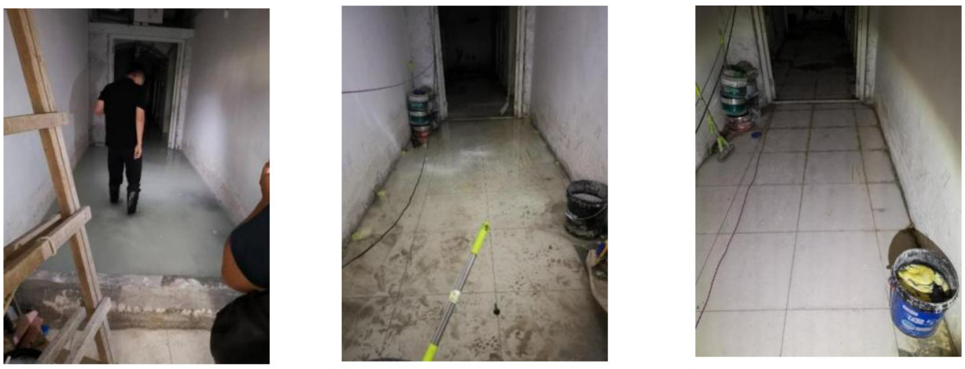


Fig. 18. Apparent effect after remediation for groundwater return condition with regard to the wet-sticking decorative layer

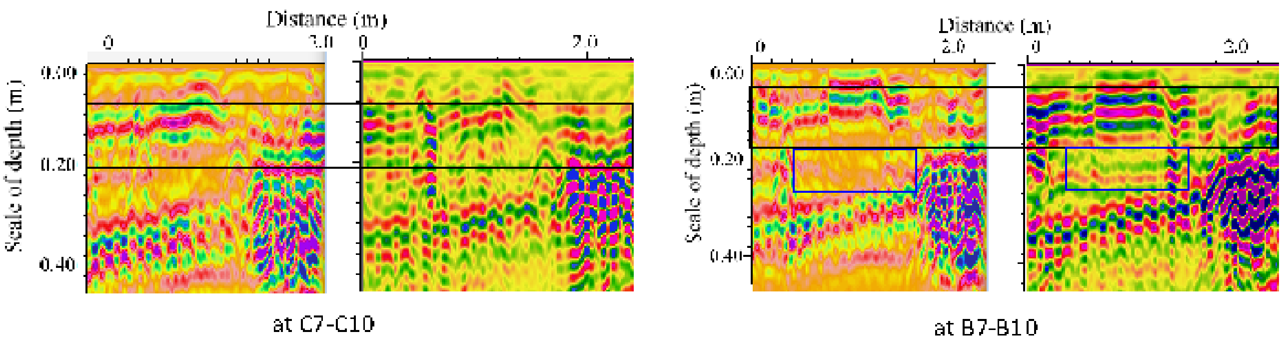


Fig. 19. Ground penetrating radar detection results before and after remediation (before remediation — on the left and after remediation — on the right)

Fig. 20. Borehole coring at B10 after remediation for ground water return condition with regard to the wet-sticking decorative layer

serve as an important reference for identifying the leakage path.

(5) The ground penetrating radar has a high detection efficiency and is suitable for large-scale detection. The ultrasonic 3D scanner has a higher detection accuracy than the ground penetrating radar, but its detection efficiency is low, making it suitable for small-scale detection.

(6) Water leakage is influenced by various defects and the actual environment, and a single method often cannot accurately detect the points and paths of leakage. Different detection methods can complement and verify each other in terms of accuracy and depth of detection as well as objects they detect. This helps enhance disease identification and accuracy, ultimately achieving the goal of precise grouting.

The combined detection device for detecting leakage points behind the decorative layer proposed herein is the subject of a patent application (#ZL 2022 2 2739345.1).

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ИССЛЕДОВАНИЕ ОБНАРУЖЕНИЯ И УСТРАНЕНИЯ ПРОТЕЧЕК В КОНСТРУКЦИИ СТАНЦИИ МЕТРОПОЛИТЕНА

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Аннотация
Введение: Принимая во внимание протечки на станциях метрополитена и различные методы обнаружения протечек, изучение методов комбинированного обнаружения, подходящих для различных эксплуатационных условий, может послужить основой для устранения протечек. **Цель:** Применение различных взаимодополняющих методов обнаружения протечек, обеспечивающее более тщательный контроль в отношении точности обнаружения и глубины расположения объектов, совершенствование процедуры обнаружения и повышение точности выявления дефектов, а также обеспечение точного цементирования. **Методы:** В ходе исследования были использованы модельные испытания и применение методов обнаружения протечек в условиях эксплуатации. **Результаты:** С помощью инфракрасного детектора и прибора для обнаружения протечек воды можно более точно определить место протечки на поверхности недекоративного слоя и «мокрого» декоративного слоя. С помощью подповерхностного радиолокатора и ультразвукового сканера поперечного сечения можно лучше определить внутренние дефекты структуры недекоративного слоя и «мокрого» декоративного слоя. При условии, что декоративный слой не демонтируется, путь протечки в бетоне, а также места протечки на поверхности могут быть эффективно обнаружены с помощью радиолокатора с воздушной связью на базе промышленного эндоскопа и специально разработанной системы камер.

Ключевые слова: метрополитен, конструкция станции, протечка, комбинированное обнаружение, восстановление цементирования.