

Intelligent Identification of Synchronous Grouting GPR Detection in Shield Tunnel and Field Test Research

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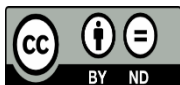


Keywords:

shield tunnel, simultaneous grouting, GPR, non-destructive testing, intelligent identification, XGBoost algorithm, field trials, archaeological excavation

ABSTRACT

In order to accurately detect the thickness of the synchronous grouting layer and its distribution in shield tunnels, this study relies on the Shanghai Rail Transit Municipal Line Airport Liaison Line project, and adopts the ground-penetrating radar to obtain the synchronous grouting information behind the shield wall. The collected data are pre-processed to perform the manual recognition and XGBoost intelligent recognition respectively. Combined with on-site excavation archaeological verification, the effectiveness of GPR system and XGBoost intelligent algorithm is analysed, and the grouting effect is evaluated. The results show that: the thickness of the grouting layer obtained by both manual recognition and intelligent recognition is within the range of from 28cm to 38cm. The XGBoost algorithm has the highest processing precision, with an accuracy rate of 96.3%, while comparing with the on-site archaeological test, it has a small error (2~3cm), and it is considered that it can be more accurately analysed for the grouting image sub-interface. The intelligent recognition results of shield grouting based on XGBoost can be fed back to guide the setting of synchronous grouting pumping pressure and slurry injection volume in subsequent projects, and provide refined guidance for secondary grouting.



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1. Introduction

With the continuous development of urban rail transit and underground engineering, shield construction has been widely used due to its many advantages [1]. During the construction process, after the shield tail is removed, an annular cavity will be formed between the stratum and the lining, namely the shield tail gap. Synchronous grouting is usually used to fill this gap [2]. That is, while the shield machine is excavating, slurry is injected into the soil layer around the tunnel through the grouting pipe to improve the stability and strength of the soil layer around the tunnel and prevent the collapse of the soil around the segment. Therefore, ensuring the quality of synchronous grouting is crucial for settlement control and construction safety.

Since synchronous grouting belongs to a hidden surface project, previous technologies cannot measure the grouting effect in real time. In recent years, after preliminary research and verification, ground penetrating radar can be used as an ideal means of synchronous grouting detection [3]. Ground penetrating radar (GPR) is a high-resolution electromagnetic scanning technology that uses the reflection of high-frequency electromagnetic beams to detect invisible targets or underground interfaces to determine their internal structure or the location of abnormal bodies and the material characteristics and distribution patterns [4]. [5] proposed a GPR based on the FDTD method. The distribution morphology of the grouting behind the tunnel wall was identified based on the two-dimensional forward modeling results of the data. [6] used a network analyzer to measure the dielectric constant of the grouting material behind the wall, which affects the detection accuracy of the ground penetrating radar. They proved that it is necessary to use different dielectric constants of different media for the recognition of the ground penetrating radar detection images for different ground penetrating radar detection frequencies. [7] analyzed the imaging law and detection effect of GPR at different frequencies and different detection times, and proved that the detection and identification effect of 400 MHz GPR is better.

After preprocessing, GPR radar images still need to be manually judged by professionals, which is slow, subjective, and unstable in accuracy. With the rapid development of intelligent algorithms, the data-driven inverse problem solving method based on deep learning provides a new idea for the recognition of GPR detection results [8]. [9] proposed an image defect recognition method based on deep learning, and constructed a mixed sample set containing images collected by detection devices and manual inspections. [10] proposed a crack intelligent recognition and quantitative analysis method based on rock mass images, which realized the automatic extraction of geometric parameters of tunnel rock mass. [11] proposed a semi-supervised deep learning method for identifying roadbed defects, and performed supervised learning on a small number of existing samples based on the YOLOv5 network. [12] proposed an unsupervised deep learning image-to-image conversion method suitable for ground penetrating radar images, which can convert real GPR images into real GPR images. The image is converted into a simulated image. [13] proposed a three-step method for automatic detection and positioning of internal defect echo features in GPR images. The proposed method can achieve a comprehensive detection accuracy of 96.99% for internal defect echo features. At present, ground penetrating radar is mostly used to detect underground diseases and defects, and is less used in detecting the thickness and distribution of synchronous grouting layers in shield tunnels [14], [15]. In the field of ground penetrating radar, the application of ensemble learning algorithms to ground penetrating radar image recognition is relatively rare.

At present, the main pattern recognition classifications include statistical pattern recognition, structural pattern recognition, fuzzy pattern recognition, support vector machine (SVM) pattern recognition, artificial neural network (ANN) pattern recognition and multi-classifier fusion. For the problem of synchronous grouting of shield tunnels detected by ground penetrating radar, machine learning methods are rarely involved [16]. Some traditional machine learning algorithms may perform poorly on large-scale data sets or complex tasks. In contrast, the ensemble learning algorithm XGBoost performs well on many data sets. Its optimization objective function and parallel processing technology make the model more accurate and efficient. It can automatically handle missing values in the data without manual processing of missing values, which simplifies the data preprocessing process. It excels at processing large amounts of data, achieving fast training speed and efficient memory usage through parallelization. It also supports various loss functions, regularization techniques, and custom optimization objective functions, enabling flexible application to different types of problems. The ensemble learning algorithm XGBoost offers advantages in accuracy, performance, scalability, feature importance analysis, handling of data quality issues, and flexibility.

Based on the Shanghai Metro Urban Rail Transit Airport Link (West Section), ground-penetrating radar (GPR) was used to measure the thickness of the synchronous grouting layer. After preprocessing, the collected data was subjected to both manual judgment and intelligent identification using the XGBoost algorithm. Finally, the two identification methods were compared with the results of on-site archaeological excavation tests, verifying the effectiveness of the proposed method.

2. Project Overview and Grouting Test

The Shanghai Metro Urban Rail Transit Airport Link Line (West Section) is Shanghai's first urban rail line to operate as a rail transit system. The project's Project 3 overview is shown in Figure 1. The project runs in an EW direction and is approximately 68.6 km long, with 56.7 km of underground sections. The project is divided into the Puxi Section, Pudong Section, and the Cross-River Section. The inter-section tunnels are constructed using the shield tunneling method. The line has 62 curves totaling 32.18 km, representing 47% of the line length. The maximum curve radius is 9,000 m, and the minimum curve radius is 520 m. The entire line is planned to utilize a double-track system and utilize CRHF urban EMU trains with a maximum design speed of 100 km/h. 160 km.

Tunnel No. 1 tunnel primarily passes through the Meifulu Shaft, Piston Ventilation Shaft, and Huajing Station, with a total length of 2,184 m. Tunnel No. 2 tunnel primarily passes through the Meifulu Shaft, Shaft No. 3, and Shaft No. 2, with a total length of 5,657 m.

3. Comparative verification of GPR detection, XGBoost intelligent identification, and on-site archaeological excavation tests

Results from on-site archaeological excavation tests indicate that the grouting layer thickness at each section ranges from 29 to 38 cm. XGBoost predicted the thickness of the grouting layer behind the shield tunnel wall to be 30 to 5 cm, with an average error of 2 to 3 cm from the field measurements. Ground-penetrating radar (GPR) detection results (human judgment) indicate a grouting layer thickness of approximately 33.5 cm, with an average error of 4 to 5 cm from the field measurements, both within the tolerance range. A comparative analysis of XGBoost's predictions, human judgment, and field measurements demonstrates that XGBoost performs well in identifying GPR detection results. Using GPR to measure the thickness of synchronous grouting slurry in shield tunnels is relatively accurate. Some discrepancies between the excavation-based measurements and the GPR results may be due to external noise during GPR testing or improper operation by workers during excavation.

4. Conclusion

After the shield tunnel wall grouting layer data detected by GPR were preprocessed using IDSP7 software, the preprocessed data were manually judged and intelligently identified by XGBoost to obtain the thickness of the synchronous grouting layer. In order to verify the accuracy of the identification results, an on-site excavation archaeological test was carried out, and three types of results were compared and analyzed. At the same time, the grouting effect was evaluated, and the main conclusions were drawn as follows:

- (1) XGBoost was used to identify the synchronous grouting layer thickness detection results of the 400MHz ground penetrating radar with a sampling accuracy of 0.01m. The accuracy of the training set reached 98.2%, and the accuracy of the validation set reached 96.3%. This shows that when the ground penetrating radar has a sampling accuracy of 0.01m, XGBoost is more accurate than GPR. The classifier classifies the radar signal more accurately and can meet the recognition requirements;
- (2) The thickness of the synchronous grouting layer behind the wall is set to be less than 0.3m as under-grouting, greater than 0.375m as over-grouting, and the rest as normal grouting. The number of under-grouting points is greater than 100, which is considered as under-grouting of the entire ring, and

the number of over-grouting points is greater than 100, which is considered as over-grouting of the entire ring. After processing the GPR detection data, it is found that the number of over-grouting points in ring 1210 is 0 and the number of under-grouting points is 0; the number of over-grouting points in ring 1215 is 75 and the number of under-grouting points is 0. Therefore, both rings detected are in the normal grouting situation;

(3) On-site excavation archaeological tests were carried out on the ring section and longitudinal section of the pipe segment, with a total of 24. There were 3 measuring points, of which a few showed over-grouting and under-grouting, while most showed normal grouting.

(4) Comparing the GPR detection results, XGBoost identification results, and on-site excavation results, it was found that the grouting thickness of the shield tunnel wall detected by the three methods was 28-38 cm. Although there was a certain error with the true value, the error was within the allowable range. This method shows a high accuracy rate in the identification and thickness detection of the grouting layer behind the shield tunnel wall;

(5) Near the grouting port, the slurry layer thickness is relatively large because the slurry is directly injected from the pipe into the shield tail gap. As the construction progresses, the slurry layer thickness is relatively thin in the area away from the grouting hole. In places such as spandrels, the pressure distribution may be different because the soil layer is supported by the spandrels, resulting in differences in the penetration depth and thickness distribution of the slurry. Under normal circumstances, a thicker slurry layer may be formed at the spandrels to strengthen the consolidation and support of the soil around the spandrels.

(6) The research results can be used to promptly detect abnormal conditions during the grouting process, provide feedback and guidance on the setting of grouting hole positions and pumping pressure in subsequent projects, and reasonably allocate slurry materials, thereby providing targeted guidance for secondary grouting.

5. References

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