Detection of grouting effect in defective areas of metro concealed tunnels in loess areas

Qingrui Chen¹, Xuanrong Zheng¹*, Xuexuan Shang², Gao Lv³, Kang Yang¹, Jiahui Qi¹ Ruilei Xue¹ and Weikang Cheng¹

¹Department of Architecture and Civil Engineering, Xi'an University of Science and Technology, Xian, Shaanxi, 710054, China
²Shaanxi Construction Engineering Group Company Limited
³Department of Civil Engineering, Xi'an Shiyou University, Xian, Shaanxi, 710065, China
*zhengxuanrong@xust.edu.cn

Abstract. The occurrence of grouting defect areas in metro concealed excavation tunnels will lead to water seepage or deformation of the tunnels, which in turn will affect the metro operation and the safety of the buildings around the metro. In order to detect the effect of grouting in defective areas of concealed tunnel, this paper introduces the principle and characteristics of seismic scattering technology, and illustrates the application of this technology in detecting the effect of grouting in defective areas of concealed tunnel in Xi'an metro line 6 from Textile City to Textile Road with the application example of seismic scattering technology. The results show that: the grouting area shows high speed anomalies in the wave velocity image, and the defect area shows low speed anomalies, and the location and morphology of the grouting area and the defect area can be determined according to the distribution of high and low wave velocity anomalies in the wave velocity image. The technology also has the features of simple operation, large detection depth and high resolution, which is an effective tool for future urban metro construction and environmental impact detection and evaluation.

1. Introduction
Because loess has the characteristics of loose, macropore and vertical joint development [1], the stress and deformation of tunnels built in loess stratum are obviously different from those in other soils. Therefore, it is particularly important to prevent the collapse of the excavation face and control the surface settlement by grouting reinforcement in the construction of subway shallow excavation in loess area.

Many domestic and foreign researchers have tried to evaluate the quality of reinforcement in grouted areas by using many different detection methods, but most of them focus on methods such as geological radar [2-4], electromagnetic wave CT [5-6], high-density electrical method [7], etc. The research on seismic scattering technology, a new type of physical detection method, is not common.

Based on the clarification of the principle and characteristics of seismic scattering technology, this paper presents in detail the application of seismic scattering technology in the section of Xi'an Metro Line 6 from Fang 2nd Road to Textile City, proving that seismic scattering technology is an effective means of detecting road hazards in urban interference environment.
2. Seismic scattering technology
The seismic scattering technology uses an artificial seismic source to excite seismic waves at the surface, and the seismic waves will scatter and reflect if they encounter a wave impedance change interface such as cavity or loose in the process of subsurface propagation [8], by receiving the reflected and scattered waves within the subsurface non-uniform medium to image the geological interface and stratigraphic wave velocity to show the fine subsurface structure, as shown in Figure 1.

![Figure 1. Schematic of the principle of seismic scattering technology.](image)

3. Engineering and Geology Overview
This paper is based on the second phase of the Xi'an Metro Line 6 project, the interval from Textile Second Road to Textile City Station. Because f6 ground crack twice through this interval. Therefore, the interval tunnel is constructed by a combination of shield structure, concealed excavation and open excavation methods. The section studied in this paper is a concealed excavation section.

In general, the concealed tunnel excavation section is large, and the stratum is relatively broken over the f6 north ground fracture section, and the palm surface is easy to collapse. In order to reduce the construction risk, a cement and water glass double slurry is used for full section grouting reinforcement from the tunnel and 3m beyond the outer contour line. The layout of the grouting holes is shown in Figure 2. To find the missed grouting defect areas for further treatment, this paper uses seismic scattering technique to detect the effect of grouting reinforcement.

![Figure 2. Cross-sectional layout of full-section grouting holes.](image)

![Figure 3. Monitoring line location diagram.](image)

4. Detection engineering layout and instrumentation
C1 measurement line was arranged along the east-west direction of the municipal district residents, and C2 and C5 measurement lines were arranged in the northeast-southwest direction along the axis of the metro concealed tunnel in the municipal district yard to detect the construction disturbance area and its grouting effect in the left and right lines of the metro line 6 respectively. Along the left and right sides of the new medical road, C4 and C3 measurement lines were arranged. The survey line layout is shown in Figure 3. The survey line mileage table is shown in Table 1.
5. Analysis
The stratigraphic wave velocity distribution image reflects the wave velocity distribution characteristics of the stratum, whose vertical coordinate is the depth, horizontal coordinate is the mileage, and the imaging physical quantity is the stratigraphic longitudinal wave velocity. The red and yellow colours in the image indicate high wave velocity, while light blue and dark blue indicate low wave velocity. The high wave velocity indicates the hard soil layer, while the low wave velocity indicates the soft soil layer, which is the main criterion for the identification of subsurface voids, loose and weak zones.

The geological interface offset image mainly reflects the geometry of the stratigraphic interface, the boundary of the extraction zone and the tectonic characteristics, i.e. the burial depth and production of the stratigraphic lithological interface. The vertical coordinate is the depth, the horizontal coordinate is the mileage, and the physical quantity of imaging is the scattering intensity. In the figure, red and yellow indicate positive scattering, which is the interface of increasing wave impedance; dark blue and light blue indicate negative scattering, which is the interface of decreasing wave impedance; green, yellow and sky blue layers are weak scattering areas, which indicate the area of more stable wave impedance.

6. Test results
A total of 5 total survey lines were explored to a depth of 40m, and the stratigraphic wave velocity distribution map and geological offset map were obtained to analyze the grouting condition and other geological diseases in this range.

6.1. C1 measuring line test results
The wave velocity distribution and geological interface pattern of C1 line are shown in Figure 4 and Figure 5.

![Figure 4. Distribution of stratigraphic wave velocity of C1 detection line.](image1)

![Figure 5. Geological offset map of C1 detection line](image2)

The wave velocity image in the range of burial depth within 20m at mileage 0-8m is significantly higher than other areas, presumably this is the grouting area; at mileage 14-25m there is an obvious low velocity area at burial depth 25-34m, which corresponds to the construction drawing and can be known as the tunneling response. The offset image shows that the stratigraphic interface is nearly horizontal.
At mileage 14-25m, there is a layer with low impedance at 25-34m burial depth, which is consistent with the low velocity zone in the wave velocity image and is a tunneling response.

In summary, no low velocity anomaly zone is found in the grouting location within the measurement area, and the grouting effect is good; no other low velocity anomaly zone is found except for the tunnel low velocity anomaly reaction, and no geological disease is found in this area.

6.2. C2 measuring line test results
The wave velocity distribution of the stratigraphic layers and the geological interface pattern of the C2 survey line are shown in Figure 6 and Figure 7. The survey line runs from northeast to southwest, 16 m long and 40 m deep. The colour layers in the wave velocity image correspond to the soil layers in the geological survey report, and there is no abnormal zone of wave velocity. The offset image shows that the stratigraphic interface is nearly horizontal. There is no layer with low wave impedance in this section, and there is no low velocity anomaly zone in the wave velocity image. In summary, no geological diseases were found in this area.

6.3. C3 measuring line test results
The wave velocity distribution of the stratigraphic layers and the geological interface morphology of the C3 survey line are shown in Figure 8 and Figure 9. The survey line is north to south, 60 m long and 40 m deep. The colour layers in the wave velocity image correspond to the soil layers in the geological survey report, and there are no wave velocity anomalies. The offset image shows that the stratigraphic interface is nearly horizontal. There is no layer with low wave impedance in this section, and there is no low velocity anomaly zone in the wave velocity image. To sum up, no geological diseases are found in this area.
6.4. C4 measuring line test results
The wave velocity distribution of stratigraphy and geological interface pattern of the C4 survey line are shown in Figure 10 and Figure 11. The line is from north to south, 30 m long and 40 m deep, and the wave velocity image shows a dark blue area at mileage 10-12 m and burial depth 14 m-20 m, which is obviously a low velocity area. The corresponding offset image also shows that there is a layer with low wave impedance here, which is presumed to be a sparse anomaly. The low impedance layer in the offset image is relatively large, with the mileage in the range of 8-18m, so the sparse area here may be larger.

6.5. C5 measuring line test results
The wave velocity distribution and geological interface pattern of the C5 line are shown in Figure 12 and Figure 13. The line runs from northeast to southwest, 58 m long and 40 m deep, and the wave velocity map shows high wave velocity at mileage 0-2 m, which is presumed to be influenced by grouting. The offset image shows that the stratigraphic interface is nearly horizontal. There is no layer with low wave impedance in this section, and there is no low velocity anomaly in the wave velocity map. In summary, no geological lesions were found in this area.

7. Conclusions
By analyzing the stratigraphic wave velocity distribution and the geological offset map, we can draw the following conclusions:

The velocity images obtained from the seismic scattering technique detection reflect the tunnel grouting defect area intuitively, and the method has the advantages of high resolution, large detection
depth, no damage to the road surface and high efficiency, which effectively determines the location and scale of the grouting plus solid as well as the defect area.

In the wave velocity image of the C4 line, there is a dark blue area in the range of mileage 10-12m and burial depth 14m-20m, which is obviously a low velocity area. The corresponding offset image shows that there is a layer with low wave impedance here, which is presumed to be a grouting defect area.

The defective area should be reinforced by timely grouting and by secondary detection until the defective area disappears, indicating a better grouting effect.

References
[1] Fang, T. (2012) Wet sinking loess tunnel substrate reinforcement treatment technology. New Technology and New Products in China, 7:43–43.
[2] Ge, S.C., Chen, J., Zhao, Y.H. (2011) Wavelet analysis of engineering grouting radar images and detection effect study. Advances in Geophysics, 26(03):1101-1106.
[3] Bricheva, S.S., Dubrovin, I.O., Lunina, O.V. (2021) Numerical simulation of ground-penetrating radar data for studying the geometry of fault zone. Near Surface Geophysics, 19(2): 261-277.
[4] Carmine, M., Claudia, C. and Felice, U.V. (2021) Ground Penetrating Radar as a Functional Tool to Outline the Presence of Buried Waste: A Case Study in South Italy. Sustainability, 13(7): 3805-3805.
[5] Peng, Y.L., Hu, Y.W., Zhang, L.(2011) Applied experimental study on the evaluation of grouting effect in complex mining areas by using integrated physical exploration method. In: Proceedings of 2011 AASRI Conference on Information Technology and Economic Development. Kuala Lumpur .pp. 255-260
[6] Peng, D., Liu, W. (2019) Means and methods of karst special survey for Kunming rail transit. Tunnel Construction (English and Chinese), 39(S2):269-282.
[7] Qi, D., Niu, J.J. (2021) Application of high density resistivity method in landslide detection. IOP Conference Series: Earth and Environmental Science, 734(1).
[8] Xi, J.J., Cui, D.D. (2021) Research on Comprehensive Exploration Technology of Underground Soil Karst Cave. IOP Conference Series: Earth and Environmental Science, 2021, 660(1): 012012-.
[9] Yu, L., Wang, G.Q., Yuan, Z.M. (2013) Application of seismic scattering profile technique in the shallow fine exploration. Geophysical Prospecting for Petroleum, 52 (1) : 43—48.