# Serviceability Evaluation of Shield Tunnel in Shanghai Metro Line 1 based on 3D Laser Scanning

Zhang Wei[1,2], Li ShengTeng[1,2], Xue YaDong[1,2]
[1] Key Laboratory of Geotechnical and Underground Engineering (Tongji University), Ministry of Education, Shanghai 200092, China.
[2]Department of Geotechnical Engineering College of Civil Engineering, Tongji University, Shanghai 200092, China.
Email : 2132559@tongji.edu.cn, 2032590@tongji.edu.cn

ABSTRACT: With the development of urbanization, the construction of subways in major cities continues to advance to meet growing traffic demand. However, during the operating life of a subway, the tunnel will inevitably suffer from crack, leakage, block, or other diseases, which can severely affect the serviceability of the entire tunnel. Tunnel serviceability index (TSI) can be used to evaluate the health of subway shield tunnels during the operation period. However, as a sub-indicator of TSI, the circumferential deformation around the tunnel is still mainly measured in an artificial way. In this study, a 3D laser scanning-based method is proposed to quickly measure the diameter change of the tunnel circumference. Firstly, a mobile laser detection vehicle is adopted to collect the laser point cloud data of the tunnel surface in Shanghai Metro Line 1. Secondly, data denoising and grayscale images generation are performed, the denoised point cloud data is used to calculate the convergence deformation of the tunnel cross-section by ellipse fitting. Thirdly, combined with other operating tunnel health indicators, TSI can be calculated to evaluate the health of each section of the tunnel. This method can accurately and quickly obtain the circumferential diameter deformation of the tunnel, which is beneficial to TSI update and tunnel health detection.

KEY WORDS: Structural health assessment; TSI; 3D mobile laser scanning; Point cloud.

## 1 INTRODUCTION

To quantify the health condition of shield tunnels in operation, Li proposed the tunnel serviceability index (TSI) [1]. According to TSI, maintenance personnel can evaluate the service performance of tunnels in sections through many monitoring data. Besides, it is convenient to locate the diseases, which can benefit for the remediation of specific diseases. The TSI index includes several sub-indices such as leakage area, total spalling area, total crack length, average relative settlement, average differential settlement, and average circumferential diameter change. Among them, the common practice of the average circumferential diameter change is to use a manual total station to measure at fixed points and record the measurement information in inspection reports. However, this type of detection method has several defects such as high labor cost, low efficiency, and strong subjectivity. To overcome the shortcomings of the above manual method, automated and intelligent detection methods has become an important research direction in recent years [2].

The 3D scanning technology can quickly obtain the 3D coordinate information of an object surface, which is a kind of stereo measurement technology. Compared with traditional measurement technology such as coordinate measuring machine (CMM), it can complete the measurement of complex objects, which is characterized by non-contact, high precision, fast speed, can greatly save time and cost. These advantages make 3D scanning technology widely used [3].

Mobile laser scanning technology is a new measurement method with a laser scanner as the main detection device, and the device can scan the surface of the tunnel lining at a high speed in a non-contact form [4]. In recent years, a lot of research have been carried out on the tunnel deformation measurement based on laser scanning technology. Arastounia used a mobile lidar device to perform laser scanning on subway tunnels and extracted the long and short axes of the tunnel cross-section [5]; Zhou et al. used mobile 3D laser scanning technology combined with machine learning algorithms to quantify and visualize tunnel diseases [4]. Nuttens et al used 3D laser scanning technology to monitor tunnel's ovality under the action of estuary tides [6]. Xie proposed a 3D modeling algorithm for tunnels based on ground 3D laser scanning to visualize tunnel deformation [7]; Sun used a mobile laser measurement system to analyze and visualize the deformation of the tunnel section [8].

This paper is organized as follows. Inspection equipment and data acquisition process of Shanghai metro shield tunnels are introduced in Section 2. Serviceability assessment of operating tunnels is presented in Section 3, and conclusions are discussed in Section 4.

## 2 DATA ACQUISITION

### *2.1 Inspection equipment*

In order to obtain the 3D point cloud data of the tunnel shape, the ZF PROFILER 9012 inspection vehicle was used to collect point cloud data for Shanghai Metro Line 1. The inspection vehicle is equipped with Z+F analyzer, 3D laser scanner, two batteries and other accessories. The specific parameters are shown as Table 1.

Table 1. Inspection vehicle parameters.

| Model number | ZF PROFILER 9012 |
|---|---|
| Scanning method | Single-axis rotating |
| Scanning range | 360° |
| Farthest measuring distance | 119m |
| Nearest measurement distance | 0.3m |
| Distance resolution | 0.1mm |
| Angular resolution | 0.0088° |

| | |
|---|---|
| Maximum measurement frequency | 200Hz |
| Maximum measuring speed | $10^6$ p/s |
| Measurement accuracy (5m) | 0.4mm |
| Memory capacity | 128+32+32GB |
| Power supply | 100-240V AC |

In order to make the detection results more obvious, the detection equipment detected the subway shield tunnel from Caobao Road to People's Square Station of Shanghai Line 1 with the longest operating time. A total of 295 ring-width tunnel lengths were measured. The detection equipment and detection process are shown in Figure 1.

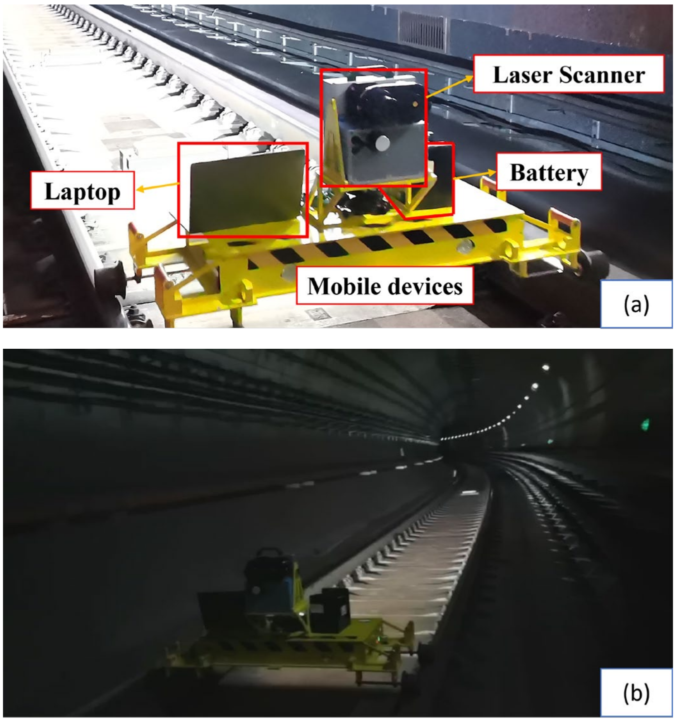



Figure 1. Point cloud data acquisition: (a). Detection equipment (b). Detection process.

### 2.2 *Data processing*

Based on laser scanning technical, the 3D discrete point cloud including spatial coordinates and intensity information is measured. Given that a large amount of noise data is included in raw point cloud data obtained from the mobile laser scanning system, it can cause accuracy errors on data analysis. Thus, the intensity threshold method and the k-means clustering algorithm are used to reduce noise for the 3D discrete point cloud. Then, the denoised LAS file is imported into Cloud Compare software to render 3D model based on the point cloud intensity. The rendering result is shown as Figure 2.

In order to obtain the circumferential diameter deformation of the tunnel, the cloud model is divided into 295 sections according to the ring width. Then, the point cloud of 295 rings is further divided into 61 units per five rings to reduce subsequent computation.

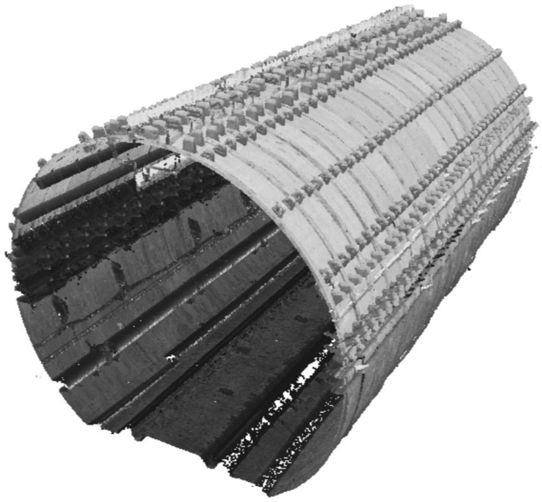


Figure 2. 3D tunnel point cloud after denoising and rendering

Due to the influence of surrounding ground and subway vibration, circumferential deformation (the interpolation of the deformed tunnel diameter and the tunnel's design diameter) of the tunnel lining is inevitable [9]. The design shape of the subway tunnel is an ellipse, the equation can be expressed as equation 1.

$$Ax^2 + Bxz + Cz^2 + Dx + Ez + 1 = 0 \tag{1}$$

Coefficient matrix: $M = [A, B, C, D, E, 1]$ ; Ellipse fitting matrix composed of coordinate data: $X = [x^2, xz, z^2, x, z, 1]^T$. Based on the principle of least squares, the best fitting circle of the point cloud section can be obtained, and the distance between the farthest points in the lateral direction is calculated as the circumferential diameter after tunnel deformation. The design diameter of a tunnel is 5.5m, and the lateral convergence of the tunnel can be obtained. The maximum diameter deformation reaches 29.1335mm during the 295 rings width. Average convergence ratios are shown in Figure 3.

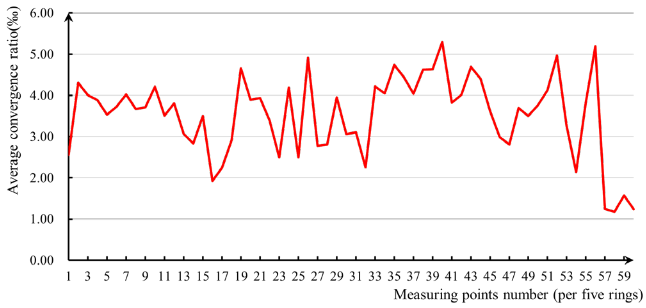



Figure 3. Average convergence ratio (295 rings)

Through the coordinate conversion, the 3D point cloud can be transformed into a two-dimensional point cloud, and other apparent diseases can be identified through machine learning algorithms [10]. Due to the space limitations, this study refers to the use of point clouds to detect the lateral convergence of tunnels.

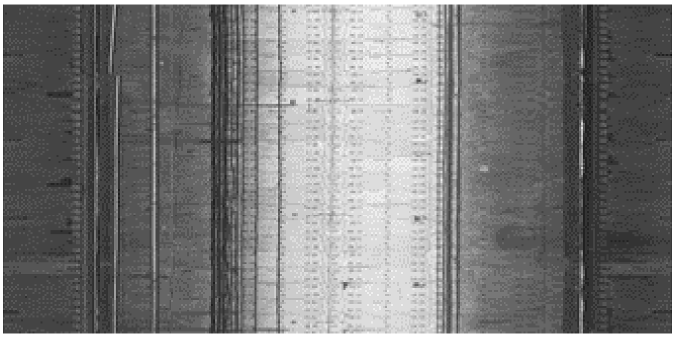


Figure 4. 2D grayscale image

## 3 TUNNEL SERVICE PERFORMANCE EVALUATION BASED ON TSI

Health assessment of shield tunnels is one of the key issues of structural maintenance during tunnel service life. Traditionally, the health condition of shield tunnels is graded according to certain types of tunnel distresses, such as convergent deformation, settlement, cracks, water leakage, etc. However, the overall condition cannot be directly assessed because it often depends on the decisions and evaluations of experts in the actual situation. Thus, Li proposed 'tunnel serviceability index' (TSI) using regress method based on the actual manual detection data of Shanghai Metros.

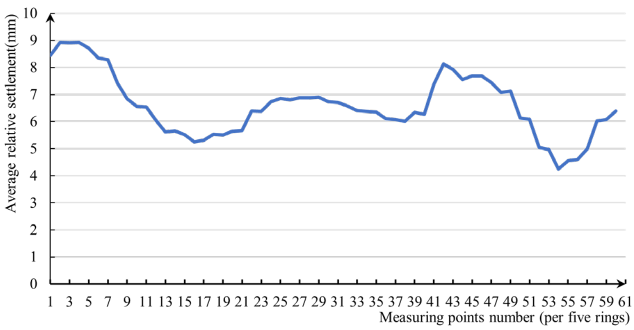
$$TSI = 5.23 - 0.09C_{ave} - 0.08d_l - 0.5d_s - 0.05d_c - 0.16\sqrt{S_{ave}} - 0.01S_{\mathrm{diffave}} \tag{2}$$

Where $C_{ave}$ is average circumferential diameter change; $d_l$ is total leakage area; $d_s$ is total spalling area; $d_c$ is total crack length; $S_{ave}$ is average relative settlement; $S_{diffave}$ is average differential settlement. Based on TSI method, tunnel structure health status is classified into five grades:

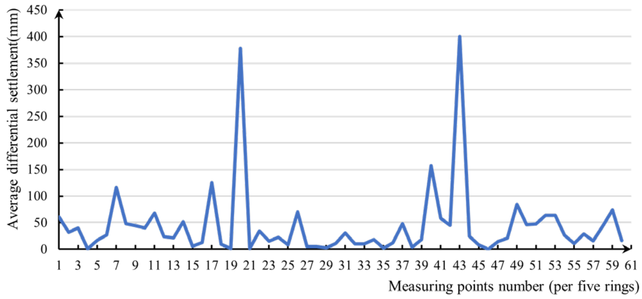
Table 2. Corresponding relationship between TSI and tunnel health

| TSI | 0~1 | 1~2 | 2~3 | 3~4 | 4~5 |
|---|---|---|---|---|---|
| grades | Instability | Unavailable | Deterioration | Degradation | Normal |

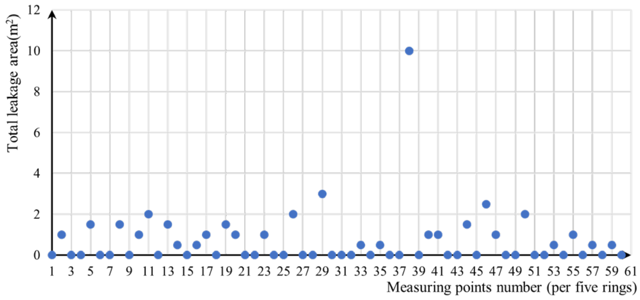
For Shanghai Metro Line 1, indexes: $d_l, d_s, d_c, S_{ave}, S_{diffave}$ were detected periodically based on manual periodic inspection. The results are shown as Figure 5. Based on the six evaluation indicators, the TSI value in the 295 ring is calculated according to Formula 2, and the service performance of the tunnel is evaluated according to Table 2.



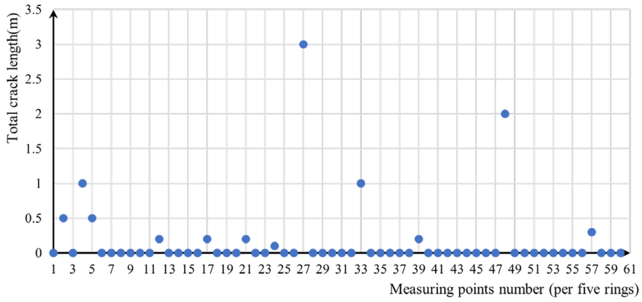

(a)



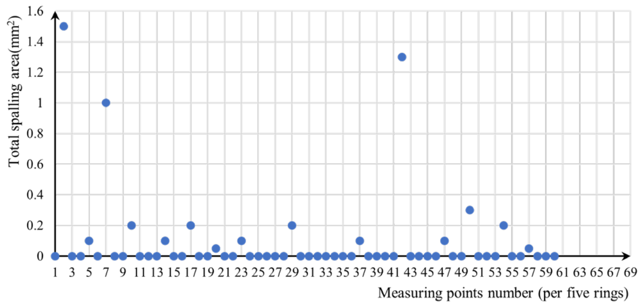

(b)




(c)




(d)




(e)

Figure 5. Manual detection data (295 rings): (a) Average relative settlement (mm); (b) Average differential settlement; (mm); (c) Total spalling area ($m^2$); (d) Total crack length (m);(e) Total spalling area($m^2$).

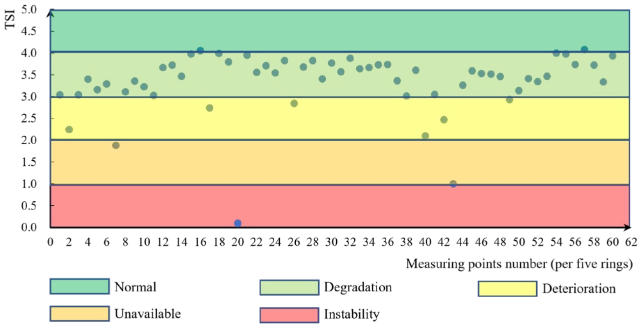



Figure 6. Tunnel service performance evaluation (295 rings)

As shown in Figure 6, one of the tunnel detection areas is in unstable condition, two are in unavailable condition, six are in deterioration condition, two are in normal, and others are in degradation stage. The overall condition of the tunnel is in benign operation stage. The 35th to 40th, 100th to 105th, and 215th to 220th rings may require manual maintenance. Based on data analysis, the TSI index is mostly affected by the average differential settlement. The unstable state of the tunnels in the 35th to 40th rings is caused by the excessive differential settlement, and maintenance personnel should pay more attention on these areas. The detection result is close to the actual result, which shows the practicability of the method.

## 4 CONCLUSION

The main conclusions of this study are as follows:

- In this paper, 3D laser scanning technology combined with TSI method is used to evaluate the health condition of Shanghai Metro Line 1. The results are consistent with the manual inspection
- Compared with the traditional artificial detection method, the 3D laser scanning technology is more efficient and can greatly save manpower and material resources.
- Based on the TSI method, the service performance and health of operational tunnels can be comprehensively evaluated. Maintenance personnel just need to pay more attention to the areas with high TSI values, not the entire tunnel.

## ACKNOWLEDGMENTS

This work was supported by National Natural-Science Foundation of China (Grant No.52078377) and Key Field Science and Technology Project of Yunnan Province (Grant No. 202002AC080002)

## REFERENCES

[1] Li, X., Lin, X., Zhu, H., Wang, X., & Liu, Z. (2017). Condition assessment of shield tunnel using a new indicator: the tunnel serviceability index. *Tunnelling & Underground Space Technology, 67*(aug.), 98-106.

[2] Liu, X.，Chen, Y.，& Liu, X. (2021). Rapid detection technology of deformation of shield tunnel section based on laser scanning［J］. *Journal of Traffic and Transportation Engineering*，2021，21(2), 10.

[3] Yuan, X. 3D laser scanning point cloud data processing and application technology. (Doctoral dissertation, Nanjing University of Science and Technology).

[4] Chen, J. (2021). A novel approach to automated 3d spalling defects inspection in railway tunnel linings using laser intensity and depth information. *Sensors*, 21.

[5] Mostafa, A. (2016). Automated as-built model generation of subway tunnels from mobile lidar data. *Sensors*, 16(9), 1486.

[6] Nuttens, T., Stal, C., Backer, H. D., Schotte, K., Bogaert, P. V., & Wulf, A. D. (2014). Methodology for the ovalization monitoring of newly built circular train tunnels based on laser scanning: liefkenshoek rail link (belgium). *Automation in Construction, 43*(jul.), 1-9.

[7] Xie, X., Lu, X., Tian, H., Ji, Q., & Li, P. (2016). Development of a modeling method for monitoring tunnel deformation based on terrestrial 3d laser scanning". *Chinese Journal of Rock Mechanics and Engineering_, _ _000_* (011), 2214-2224.

[8] Sun, H., Liu, S., Zhong, R., & Du, L. (2020). Cross-section deformation analysis and visualization of shield tunnel based on mobile tunnel monitoring system. *Sensors* (Basel, Switzerland), 20(4).

[9] Zhou, M., Chen, W., Zhang, D., & Huang, H. (2021). Operating period of shield tunnel structure disease automated detection and 3 d visualization. *Journal of basic science and engineering*, 29(5), 15.

[10] Huang, H., Cheng, W., Zhou, M., Chen, J., & Zhao, S. (2020). Towards automated 3d inspection of water leakages in shield tunnel linings using mobile laser scanning data. *Sensors*, 23.