Grey Correlation Analysis of Factors Influencing the Stability of Loess Strata in Shield Tunneling

Haijun Zhao[1], Heyi Liu[2,*], Jiangrong Pei[2] and Tiannan Chen[2]

[1]Shandong Huake Planning and Architectural Design CO., LTD., Liaocheng, 252000, China
[2]China Institute of Water Resources and Hydropower Research, Beijing, 100048, China

*Corresponding author E-mail: heyiliu0914@163.com

Abstract. In the context of shield tunneling through loess strata, this study utilizes a refined simulation model in FLAC3D to calculate a total of 30 parameters associated with five factors influencing the maximum displacement of the surrounding rock. Through grey correlation analysis, the impact of each factor on tunnel stability is assessed. The results indicate that the maximum displacement of the surrounding rock exhibits a decreasing trend with an increase in the silo pressure, grouting material strength, and soil deformability, while it shows an increasing trend with greater tunnel depth and soil density. Both tunnel depth and soil density exhibit grey correlation coefficients exceeding 0.9, establishing them as the predominant factors influencing tunnel stability. Silo pressure, grouting material strength, and soil deformability all demonstrate grey correlation coefficients of approximately 0.5, designating them as secondary factors in this analysis.

Keywords: Loess strata; Grey correlation analysis; Sensitivity analysis; Surrounding rock displacement; FLAC3D.

1 Introduction

With the rapid development of urbanization, the demand for and utilization of underground spaces have been steadily increasing. Shield tunneling, as a significant technology in the field of underground engineering, is widely employed in transportation, water resources, and other sectors to meet the growing need for underground infrastructure. However, as urban expansion accelerates and infrastructure construction intensifies, engineering sites often encounter complex geological conditions, including loess strata. This complexity adds a considerable challenge to the design and construction of tunnel projects [1].

As one of the predominant geological conditions in the northwestern region of China, loess strata exhibit unique engineering geological characteristics that exert a profound impact on the design and construction of shield tunneling projects [2]. The stability analysis of shield tunneling projects within loess strata involves not only intricate geological features but also necessitates the consideration of the complex interplay among numerous influencing factors [3]. The ultimate success or failure of tunnel

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engineering hinges on the comprehensive effects of these factors [4]. Against this backdrop, grey correlation analysis, serving as a multifaceted evaluation method for multiple factors, offers a potent tool for unraveling the intrinsic connections among these factors [5][6]. Grey correlation analysis, grounded in grey system theory, represents a multifactorial comprehensive evaluation method that can be effectively applied to address issues characterized by incomplete or uncertain information [7]. In the context of tunnel stability concerns, grey correlation analysis can be employed to quantify the interdependencies among various influencing factors, thereby identifying which factors hold greater sway over tunnel stability [8].

In order to ensure safe and efficient excavation during shield tunneling in loess formations, it is essential to consider the various factors influencing tunnel stability. Due to the complexity of loess formations, the multitude of factors requiring assessment adds to the challenge. To simplify practical application, it is imperative to identify the primary controlling factors affecting tunnel stability. However, there is currently limited research by scholars specifically addressing shield tunneling in loess formations, resulting in a lack of awareness regarding factors sensitively impacting tunnel stability in practical engineering. To address these issues, this paper, set against the backdrop of a tunneling project in a loess formation, utilizes a refined numerical simulation model based on FLAC3D [9][10][11]. The study combines grey relational analysis with numerical simulation and real engineering cases to investigate key factors influencing the stability of shield tunnels in loess formations. These factors encompass geological conditions, grouting materials, shield machine parameters, among others. Through sensitivity analysis of these factors, the main contributors to tunnel stability are identified. This research aims to provide a more reliable basis for the design and construction of engineering projects, offering theoretical and technical support for the safe and smooth progress of the projects.

2 The principles of grey correlation analysis

Grey correlation analysis, a constituent of the Grey System Theory, provides a powerful means to identify correlations between various factors of change (comparison factors) and a reference factor, even when data resources are limited. The magnitude of correlation, expressed as correlation coefficient, signifies the strength of the relationship between the comparison factors and the reference factor. The analytical procedure involves the following specific steps: initially, the data sequences for each factor are standardized to imbue the sequences with 'comparability,' 'proximity,' and 'polarity consistency,' thereby forming a Grey correlation factor space. Subsequently, the difference information between the sequences is ascertained, creating a difference information space. Using this difference information space, a measure of difference information comparison, referred to as Grey correlation coefficient, is established and subsequently ranked. Ultimately, this process yields the sequential relationships among the factors.

2.1 Data matrix and reference data matrix

Considering the various influencing factors (such as silo pressure, grouting material strength, tunnel depth, soil deformability, etc.) on the stability of shield tunnels within loess strata, we form a comparison column *X*, denoted as $X=[X_1, X_2, X_3, \ldots, X_\mathrm{m}]$, and the corresponding stability parameters for the tunnels serve as the reference column *Y*, denoted as $Y=[Y_1, Y_2, Y_3, \ldots, Y_\mathrm{m}]$. Each factor in columns *X* and *Y* can take on several values, represented as $X_i=[X_i(1), X_i(2), X_i(3), \ldots, X_i(\mathrm{n})]$ and $Y_i=[Y_i(1), Y_i(2), Y_i(3), \ldots, Y_i(\mathrm{n})]$, respectively. The matrix form of these columns is as follows:

$$X=\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix}=\begin{bmatrix} x_1(1) & x_1(2) & \cdots & x_1(n) \\ x_2(1) & x_2(2) & \cdots & x_2(n) \\ \vdots & \vdots & \ddots & \vdots \\ x_m(1) & x_m(2) & \cdots & x_m(n) \end{bmatrix} \tag{1}$$

$$Y=\begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_m \end{bmatrix}=\begin{bmatrix} y_1(1) & y_1(2) & \cdots & y_1(n) \\ y_2(1) & y_2(2) & \cdots & y_2(n) \\ \vdots & \vdots & \ddots & \vdots \\ y_m(1) & y_m(2) & \cdots & y_m(n) \end{bmatrix} \tag{2}$$

Where 'm' represents the number of factors influencing tunnel stability, and 'n' denotes the number of varying values for each factor. Due to the dissimilar units and significant differences in magnitude between the factors in comparison column X and the corresponding reference column Y, direct comparisons are infeasible. Therefore, it is imperative to transform the raw data to render it comparable, necessitating the dimensionlessization of the matrices. Commonly employed methods include initialization, normalization, interval relative value transformation, and standardization. In this study, we employ interval relative value transformation, resulting in the following:

$$X_i^{'}=[X_i^{'}(1), X_i^{'}(2), \cdots, X_i^{'}(n)] \tag{3}$$

In the equation:

$$X_i^{'}(j)=\frac{X_i(j)-\min\limits_j X_i(j)}{\max\limits_j X_i(j)-\min\limits_j X_i(j)} \tag{4}$$

Simultaneously, the reference column Y also undergoes interval relative value transformation, thus rendering the original sequences dimensionless.

2.2 Grey correlation coefficient and grey correlation degree

The essence of grey correlation analysis lies in assessing the similarity of geometric shapes between data sequences. The closer the curves, the greater the degree of correlation between the corresponding sequences. Therefore, the magnitude of the differences between the curves serves as the measuring scale for the degree of correlation. The correlation coefficient can be determined using the following formula:

$$\gamma_{ij} = \frac{\Delta_{\min} + \zeta\Delta_{\max}}{\Delta_{ij} + \zeta\Delta_{\max}} \tag{5}$$

Here, ζ represents the resolution coefficient, which serves to enhance the significance of differences between correlation coefficients. In typical cases, ζ is often set to 0.5. The calculation of grey correlation difference information is determined using the following formula:

$$\Delta_{ij} = \left| Y_i^{'}(j) - X_i^{'}(j) \right| \tag{6}$$

Subsequently, this process yields the difference sequence matrix Δ. From the Δ matrix, the maximum and minimum values are extracted from all its elements:

$$\Delta_{\max} = \max(\Delta_{ij})\,;\, \Delta_{\min} = \min(\Delta_{ij}) \tag{7}$$

To obtain the Grey Correlation Coefficient matrix, we can substitute equations (6) and (7), along with the resolution coefficient, into equation (5). However, due to the relatively large number of correlation coefficients, and the scattered nature of the information, it can be challenging to compare them directly. Therefore, it is common practice to calculate the average value as the correlation degree for comparing the interrelationships among influencing factors. The correlation degree can be determined using the following formula:

$$A_i = \frac{1}{n}\sum_{j=1}^{n}\gamma_{ij} \tag{8}$$

The correlation degree falls within the (0,1) interval and represents the extent of variation between factors. The magnitude of correlation degree is merely an external manifestation of the interaction among factors. In correlation analysis, different sequence processing methods yield varying correlation degrees, with the correlation degree sequence reflecting the essence of sensitivity to influencing factors. In the correlation degree sequence, a higher correlation degree for an influencing factor indicates a greater impact on tunnel stability, signifying higher sensitivity. Conversely, a lower correlation degree suggests reduced sensitivity. By obtaining the correlation degree for each influencing factor and subsequently ranking them, we can derive the corresponding correlation sequence for these factors. This allows us to determine the primary and secondary factors affecting the stability of shield tunnels in loess strata.

3 The influence of factors on tunnel stability

3.1 Fundamental model and parameter selection

Focusing on a shield tunnel construction project within a specific loess stratum and disregarding local geological structures, we have developed a numerical simulation model based on the actual engineering design specifications for tunnel dimensions and the parameters of the tunnel boring machine. Subsequently, we conducted orthogonal computations to assess the impact of various influencing factors. The parameters for the fundamental model, as outlined in Table 1 according to the geological survey report, are as follows:

Table 1. Material parameters of the calculation model

Depth (m)	Silo pressure/initial geostress	Compression modulus of grouted backfill (MPa)	Compression modulus of Soil (MPa)	Density (kg.m^{-3})	Poisson's ratio	Cohesion (kPa)	Angle of internal friction (°)
100	97%	20	9.95	1980	0.3	30	20

The refined fundamental computational model, established using the finite difference software FLAC3D, is illustrated in Figure 1. The model extends longitudinally along the tunnel axis for a length of 60 meters, has a width of 30 meters, and a height of 60 meters. The constitutive model employed is idealized as elastic-plastic, utilizing the Mohr-Coulomb yield criterion. Z-direction constraints are applied at the bottom of the model, while X-direction constraints are applied to the two outer surfaces along the X-axis direction and Y-direction constraints to the two outer surfaces along the tunnel axis Y-direction.

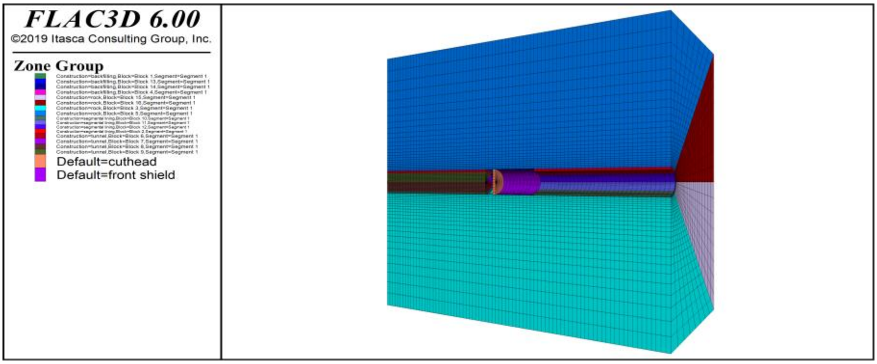

Fig. 1. Fundamental calculation model

Building upon the foundational model, we conducted grey correlation analysis to assess the sensitivity of five influencing factors: silo pressure/initial geostress, grouting material strength, tunnel depth, soil deformability, and soil density. In the current engineering practices, rock mass stability assessment primarily relies on two main criteria: surrounding rock displacement criteria and plastic zone size criteria within the surrounding rock. Among these, tunnel surrounding rock displacement is a directly measurable parameter and serves as the most immediate and explicit indicator of tunnel rock mechanics [12][13]. Therefore, in this study's grey correlation analysis, we selected the varying values of each influencing parameter to construct a comparison matrix, while the maximum displacement of the tunnel surrounding rock under the corresponding conditions served as the reference matrix.

3.2 Calculation of grey correlation degree

The variations in the maximum surrounding rock displacement with respect to each influencing factor, as obtained through numerical calculations, are illustrated in Figure 2 to Figure 6:

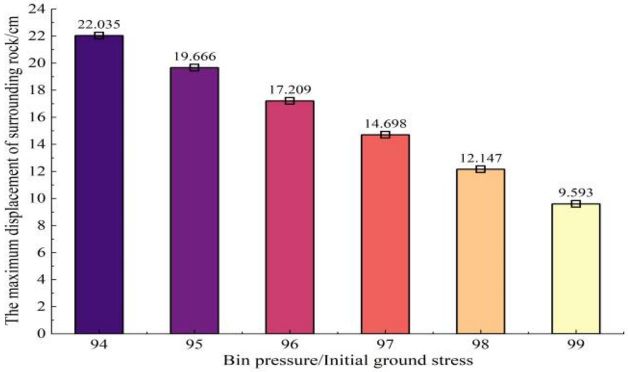

Fig. 2. Rock displacement - silo pressure

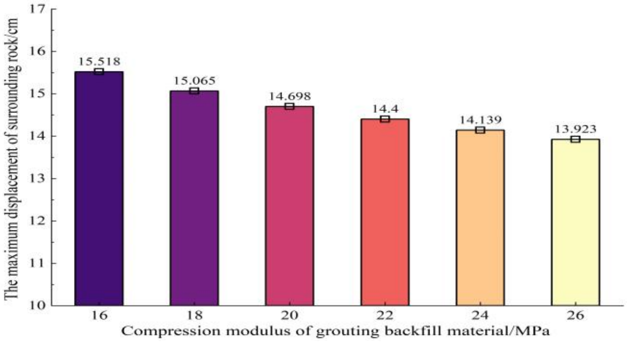

Fig. 3. Rock displacement - grouting strength

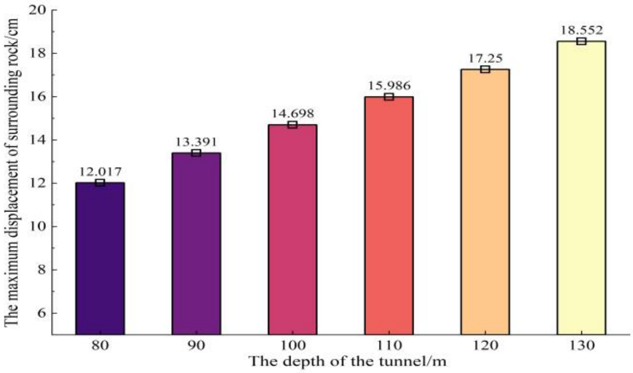

Fig. 4. Rock displacement - tunnel depth

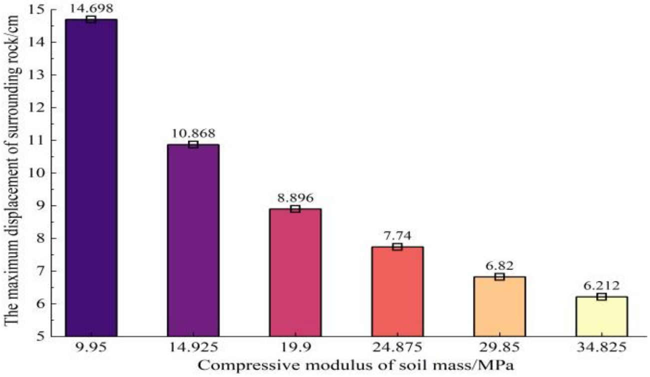

Fig. 5. Rock displacement - soil deformability

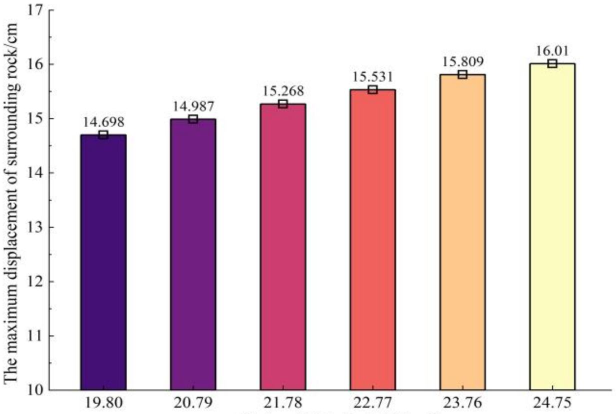

Fig. 6. Rock displacement - soil density

From the figures, it is evident that each factor has a significant impact on the maximum displacement of the surrounding rock. Notably, the maximum surrounding rock displacement exhibits a decreasing trend with increasing silo pressure, grouting material strength, and soil deformability, while it demonstrates an increasing trend with greater tunnel depth and soil density. The variation in the displacement of surrounding rock differs significantly among the factors. The sensitivity of each factor's influence on surrounding rock displacement is assessed using grey correlation analysis.

The comparison matrix *X* is as follows:

$$X = \begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_m \end{bmatrix} = \begin{bmatrix} 94 & 95 & 96 & 97 & 98 & 99 \\ 16 & 18 & 20 & 22 & 24 & 26 \\ 80 & 90 & 100 & 110 & 120 & 130 \\ 9.95 & 14.925 & 19.9 & 24.875 & 29.85 & 34.825 \\ 19.8 & 20.79 & 21.78 & 22.77 & 23.76 & 24.75 \end{bmatrix} \tag{9}$$

The reference matrix *Y* is as follows:

$$Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_m \end{bmatrix} = \begin{bmatrix} 22.035 & 19.666 & 17.209 & 14.698 & 12.147 & 9.593 \\ 15.518 & 15.065 & 14.698 & 14.4 & 14.139 & 13.923 \\ 12.017 & 13.391 & 14.698 & 15.986 & 17.25 & 18.552 \\ 14.698 & 10.868 & 8.896 & 7.74 & 6.82 & 6.212 \\ 14.698 & 14.987 & 15.268 & 15.331 & 15.809 & 16.01 \end{bmatrix} \tag{10}$$

The dimensionless comparison matrix *X′* and the reference matrix *Y′*, obtained through the interval relative value transformation method applied to the aforementioned matrices, are as follows:

$$X' = \begin{bmatrix} X_1' \\ X_2' \\ \vdots \\ X_m' \end{bmatrix} = \begin{bmatrix} 0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 \\ 0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 \\ 0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 \\ 0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 \\ 0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 \end{bmatrix} \tag{11}$$

$$Y' = \begin{bmatrix} Y_1' \\ Y_2' \\ \vdots \\ Y_m' \end{bmatrix} = \begin{bmatrix} 1 & 0.81 & 0.612 & 0.41 & 0.205 & 0 \\ 1 & 0.716 & 0.486 & 0.299 & 0.135 & 0 \\ 0 & 0.21 & 0.41 & 0.607 & 0.801 & 1 \\ 1 & 0.549 & 0.316 & 0.18 & 0.072 & 0 \\ 0 & 0.22 & 0.434 & 0.482 & 0.847 & 1 \end{bmatrix} \tag{12}$$

Subsequently, the difference sequence matrix Δ is derived as follows:

$$\Delta = \begin{bmatrix} 1 & 0.61 & 0.212 & 0.19 & 0.595 & 1 \\ 1 & 0.516 & 0.086 & 0.301 & 0.665 & 1 \\ 0 & 0.01 & 0.01 & 0.007 & 0.001 & 0 \\ 1 & 0.349 & 0.084 & 0.42 & 0.728 & 1 \\ 0 & 0.02 & 0.034 & 0.118 & 0.047 & 0 \end{bmatrix} \tag{13}$$

In the difference sequence matrix, $\Delta_{max}=\max(\Delta_{ij})=1$, and $\Delta_{min}=\min(\Delta_{ij})=0$. By selecting a resolution coefficient $\zeta=0.5$ and performing the calculations, we obtain the Grey Correlation Coefficient matrix γ as follows:

$$\gamma = \begin{bmatrix} 0.333 & 0.45 & 0.702 & 0.725 & 0.457 & 0.333 \\ 0.333 & 0.492 & 0.853 & 0.624 & 0.429 & 0.333 \\ 1 & 0.98 & 0.98 & 0.986 & 0.998 & 1 \\ 0.333 & 0.589 & 0.856 & 0.543 & 0.407 & 0.333 \\ 1 & 0.962 & 0.936 & 0.809 & 0.914 & 1 \end{bmatrix} \tag{14}$$

The Grey Correlation Degree sequence, derived from the aforementioned Grey Correlation Coefficient matrix, is as follows:

$$A = \begin{bmatrix} 0.5 & 0.511 & 0.991 & 0.51 & 0.937 \end{bmatrix} \tag{15}$$

It is evident that there are notable discrepancies in the Grey Correlation Degrees of the various factors. Tunnel depth and soil density both exhibit Grey Correlation Degrees exceeding 0.9, while the Grey Correlation Degrees of the remaining three factors hover around 0.5. This signifies that among the multitude of factors influencing the maximum displacement of surrounding rock, tunnel depth and soil density are the most sensitive and dominant factors affecting tunnel stability. Consequently, in practical engineering applications, the selection of construction sites and geological conditions directly determine whether shield tunnel construction can be conducted safely and efficiently within loess strata.

The Grey Correlation Degrees of silo pressure, grouting material strength, and soil deformability are close to each other, indicating that these three factors are all secondary factors and have a similar impact on tunnel stability. However, from Figures 2 and 3, it is evident that the maximum displacement of the surrounding rock exhibits a significant variation with changes in silo pressure. Therefore, during shield tunnel construction, special attention should be paid to variations in silo pressure.

4 Conclusion

With the background of shield tunnels in loess strata, a refined simulation model was established using numerical analysis software FLAC3D. Through grey correlation analysis, the sensitivity of five factors affecting the maximum displacement of the surrounding rock was evaluated, leading to the following conclusions:

(1). Silo pressure, grouting material strength, tunnel depth, soil deformability, and soil density all exert an influence on the maximum displacement of the surrounding rock. Notably, the maximum displacement of the surrounding rock exhibits a decreasing trend with increasing silo pressure, grouting material strength, and soil deformability, while it demonstrates an increasing trend with greater tunnel depth and soil density.

(2). Tunnel depth and soil density both exhibit Grey Correlation Degrees exceeding 0.9, while the Grey Correlation Degrees of silo pressure, grouting material strength, and soil deformability are all around 0.5. This indicates that tunnel depth and soil density are the most sensitive and dominant factors determining tunnel stability. Silo pressure, grouting material strength, and soil deformability have similar Grey Correlation Degrees and are considered secondary factors.

(3). In practical engineering, the selection of construction sites and geological conditions directly determine whether shield tunnel construction can be conducted safely and efficiently within loess strata. Apart from geological conditions that cannot be altered, the significant variation in the maximum displacement of the surrounding rock with changes in silo pressure highlights the importance of closely monitoring and managing silo pressure during shield tunnel construction.

In summary, unlike the firm rock formations, the operational state of the shield machine itself is a crucial factor influencing tunnel stability when undertaking shield tunnel construction in loess formations. Therefore, in stability analysis, it is essential to consider not only geological characteristic parameters but also the working parameters of the shield machine and the interactions among various influencing factors. Grey relational analysis has quantified the magnitude of sensitivity of each influencing factor, guiding attention to which factors should be emphasized during actual construction. This study contends that the selection of construction sites and the geological conditions are the primary controlling factors in shield tunnel construction in loess formations. The variation in soil pressure in the silo is also a variable that should be constantly monitored during the construction process. It is worth noting that, in addition to the five key factors studied in this paper, several other factors must be considered during actual construction. The use of grey relational analysis provides a method to continue evaluating the sensitivity relationships of these additional factors, posing a subject for future research.

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