Sensitivity Analysis of Factors Influencing the Stability of Loess Landslide

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Abstract. Sensitivity analysis is used to check and analyze the factors that have a greater impact on the stability of the landslide, and determine the most sensitive factors that affect the stability of the landslide. At present, the sensitivity analysis of the factors affecting the stability of loess landslides in high intensity seismic regions has not been reported. In this paper, taking a loess landslide in Wenchuan earthquake area as an example, the sensitivity of its stability factors is analyzed by using the improved grey correlation method, which provides the basis for the treatment and design of loess landslide.

1. Introduction

The stability of loess landslides is affected by many internal and external factors, such as the shape of landslides, the physical and mechanical properties of landslides, the influence of earthquakes and rainfall, etc. Sensitivity analysis is used to check and analyze the factors that have a greater impact on the stability of the landslide, and determine the most sensitive and sensitive factors that affect the stability of the landslide, so as to make the landslide prevention more targeted, and make the treatment design more safe, reliable and economic. In the past research work, some scholars have made relevant research results on the sensitivity analysis of the factors affecting the slope stability [1,2], but there is no relevant report on the sensitivity analysis of the factors affecting the stability of loess landslide in the high intensity earthquake area. In this paper, taking a landslide in Wenchuan earthquake area as an example, the sensitivity of its stability factors is analyzed by using the improved grey correlation method, which provides the basis for the treatment and design of loess landslide.

Grey relational analysis (GRA) is a kind of multi factor statistical analysis method. It can find out the correlation, main contradiction, main characteristics and main influencing factors among the random factor sequences through certain data processing for each factor to be studied in incomplete information. Therefore, it is particularly suitable for the analysis and evaluation of such limited, complex and uncertain data as landslides [3,4]. The core of grey correlation analysis method is to calculate the correlation degree. The traditional calculation method of correlation degree uses equal weight to deal with each sample, which is not in line with the more important actual situation of some samples. In this paper, the improved grey correlation analysis method is used to analyze the sensitivity of the factors affecting the stability of a landslide.
2. The principle of traditional grey correlation analysis

First, you need to specify the reference matrix \( X_j = [x_j(1), x_j(2), \ldots, x_j(n)] \), and the matrix \( Y \) of the sequence being compared, \( Y_j = [y_j(1), y_j(2), \ldots, y_j(n)] \). The matrix \( Y \) of the sequence to be compared is the matrix of the sequence under the corresponding condition of the matrix \( X \) of the reference sequence, and its matrix is expressed as follows:

\[
X = \begin{bmatrix}
X_1 \\
\vdots \\
X_n
\end{bmatrix} = \begin{bmatrix}
x_1(1) & x_1(2) & \cdots & x_1(n) \\
x_2(1) & x_2(2) & \cdots & x_2(n) \\
\vdots & \vdots & \ddots & \vdots \\
x_n(1) & x_n(2) & \cdots & x_n(n)
\end{bmatrix}
\]  
(1)

\[
Y = \begin{bmatrix}
Y_1 \\
\vdots \\
Y_n
\end{bmatrix} = \begin{bmatrix}
y_1(1) & y_1(2) & \cdots & y_1(n) \\
y_2(1) & y_2(2) & \cdots & y_2(n) \\
\vdots & \vdots & \ddots & \vdots \\
y_n(1) & y_n(2) & \cdots & y_n(n)
\end{bmatrix}
\]  
(2)

Because the original data dimension of each influencing factor is different, and the order of magnitude is also different, and there is no comparability when put together. Therefore, it is necessary to carry out numerical preprocessing for the sequence \( X_i \) and \( Y_i \), eliminate the dimension and combine the order of magnitude, and select the interval relative value transformation, and the processing method is as follows:

\[
x'_i(j) = \frac{x_i(j) - \min(x_i(j))}{\max(x_i(j)) - \min(x_i(j))}
\]

\[
y'_i(j) = \frac{y_i(j) - \min(y_i(j))}{\max(y_i(j)) - \min(y_i(j))}
\]

After dimensionless processing, the matrix of the new sequence is obtained as follows:

\[
X'_i = [X'_i(1), X'_i(2), \ldots, X'_i(n)]
\]  
(4)

\[
Y'_i = [Y'_i(1), Y'_i(2), \ldots, Y'_i(n)]
\]  
(5)

After the transformation, the sequence matrix \( X'_i \) and \( Y'_i \) are transformed as follows to obtain the difference information and form the difference sequence matrix:

\[
\Delta_y = |x'_i - y'_i|
\]

Find the maximum and minimum value of the difference matrix \( \Delta_y \):

\[
\Delta(\text{max}) = \max(\Delta_y)
\]

\[
\Delta(\text{min}) = \min(\Delta_y)
\]

The correlation between comparative factors and reference factors is expressed by correlation coefficient, and its calculation formula is as follows:

\[
\xi_{ij} = \frac{\Delta(\text{min}) + \rho \Delta(\text{max})}{\Delta_y + \rho \Delta(\text{max})}
\]

Where: \( \rho \) is the resolution coefficient, usually \( \rho = 0.5 \).

The correlation coefficient is set as an average, which is expressed as the number of correlation degrees. The calculation formula of correlation degree is as follows:

\[
\gamma_i = \frac{1}{n} \sum_{j=1}^{n} \xi_{ij} \quad i = 1, 2, \ldots, m
\]

The order of correlation degree is the order of sensitivity of influencing factors.
3. Improved grey relation analysis method

The core of grey correlation analysis method is to calculate the correlation degree [5]. The traditional calculation method of correlation degree uses equal weight to deal with each sample, and its objectivity is poor. Therefore, the distance analysis method is introduced to improve the calculation of correlation degree. The formula (11) is improved to:

$$\gamma_i = \sum_{k=1}^{n} \xi_{ik}W_k, \quad i = 1, 2, \cdots, m$$  \hspace{1cm} (11)

Where: $W_k = (W_1, W_2, \cdots, W_M)^T$ is the weight vector, and the distance analysis method is introduced for calculation.

The calculation steps of distance analysis method are as follows:

1. Establish the original data. Here, the correlation matrix is regarded as the original data, i.e. $\xi_{ij} = A$, which constitutes the following matrix:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1m} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nm} \end{bmatrix}$$  \hspace{1cm} (12)

2. Dimensionless sequence. Using the specific gravity method to eliminate the original data dimension, the data matrix is recorded as follows:

$$B = \begin{bmatrix} b_{11} & \cdots & b_{1m} \\ \vdots & \ddots & \vdots \\ b_{n1} & \cdots & b_{nm} \end{bmatrix}$$  \hspace{1cm} (13)

Where: element $b_{il} = a_{il} / \sqrt{\sum_{k=1}^{m} a_{ik}^2}, k = 1, 2, \cdots, m; l = 1, 2, \cdots, n$

3. Determine the best value and the worst value of samples.

The maximum and minimum values of each index in the data matrix are selected to form the optimal sample and the worst sample respectively. The two samples are represented by $B^+$ and $B^-:

$$B^+ = (b^+_{11}, b^+_{12}, \cdots, b^+_{1m})$$  \hspace{1cm} (14)

$$B^- = (b^-_{11}, b^-_{12}, \cdots, b^-_{1m})$$  \hspace{1cm} (15)

In formula, $b^+_{1l} = \max(b_{1l}, b_{2l}, \cdots, b_{nl}), \quad b^-_{1l} = \min(b_{1l}, b_{2l}, \cdots, b_{nl}), l = 1, 2, \cdots, n$

4. The distance from each sample point to the reference sample point is calculated by the Euclidean distance formula as follows:

$$D^+_k = \sqrt{\sum_{l=1}^{m} (b^+_{kl} - b^+_{l})^2} \quad k = 1, 2, \cdots, m;$$ \hspace{1cm} (16)

$$D^-_k = \sqrt{\sum_{l=1}^{m} (b^-_{kl} - b^-_{l})^2} \quad k = 1, 2, \cdots, m$$

5. Calculate the relative proximity from each index sample point to the optimal sample point:

$$C_k = \frac{D^-_k}{D^+_k + D^-_k} \quad k = 1, 2, \cdots, m$$ \hspace{1cm} (17)

The larger the $C_k$ is, the closer the sample point is to the optimal sample point.

6. Normalize $C_k$ to get the vector value of correlation degree weight, and the calculation formula is as follows:

$$W_k = \frac{C_k}{\sum_{k=1}^{m} C_k} \quad k = 1, 2, \cdots, m$$ \hspace{1cm} (18)

$W = (W_1, W_2, \cdots, W_M)$ is the vector of the weight.
4. Analysis on the sensitivity of factors affecting the stability of a loess landslide by improved grey correlation method

Taking a loess landslide as an example, sensitivity analysis is carried out by selecting horizontal seismic acceleration coefficient $J_H$, internal friction angle $\phi$, cohesion $c$ and volume weight $\gamma$ of landslide mass as the main influencing factors. According to the test data and parameter inversion, the benchmark values of $\phi=12^\circ$, $c=19$ kPa, $\gamma=19$ kN.m$^{-3}$ and horizontal seismic acceleration coefficient $J_H=0.05$ (seismic intensity is VIII degree) are selected. Assuming that one parameter remains unchanged and the other parameters change, six groups of different friction angle, cohesion, volume weight of landslide mass and acceleration coefficient of horizontal seismic force are selected, and the stability coefficient of landslide is calculated by unbalanced force transfer method. Table 1-4 are the calculation results of the landslide stability coefficient $F_S$.

**Table 1.** Calculation results of stability coefficient when acceleration coefficient of horizontal earthquake changes.

| $J_H$  | 0     | 0.025 | 0.05  | 0.075 | 0.1   | 0.125 |
|--------|-------|-------|-------|-------|-------|-------|
| Stability coefficient | 1.279 | 1.130 | 1.012 | 0.916 | 0.837 | 0.769 |

**Table 2.** Calculation results of stability coefficient when cohesion of slip zone soil changes.

| $c$/kPa | 9    | 12   | 15   | 19   | 21   | 24   |
|--------|------|------|------|------|------|------|
| Stability coefficient | 0.967 | 0.982 | 0.997 | 1.012 | 1.028 | 1.043 |

**Table 3.** Calculation results of stability coefficient when internal friction angle of sliding zone soil changes.

| $\phi$/(°) | 7    | 9    | 11   | 12   | 15   | 17   |
|------------|------|------|------|------|------|------|
| Stability coefficient | 0.580 | 0.723 | 0.867 | 1.012 | 1.160 | 1.311 |

**Table 4.** Calculation results of stability coefficient when the weight of sliding body changes.

| $\gamma$/kN.m$^{-3}$ | 13   | 15   | 17   | 19   | 21   | 23   |
|----------------------|------|------|------|------|------|------|
| Stability coefficient | 1.055 | 1.037 | 1.023 | 1.012 | 1.004 | 0.996 |

The value of each influencing factor is selected as the reference sequence matrix, and the corresponding stable coefficient value is selected as the comparison sequence matrix.

\[
X = \begin{bmatrix}
X_1 \\
X_2 \\
\vdots \\
X_n \\
\end{bmatrix} = \begin{bmatrix}
0 & 0.025 & 0.05 & 0.075 & 0.1 & 0.125 \\
9 & 12 & 15 & 19 & 21 & 24 \\
7 & 9 & 11 & 12 & 15 & 17 \\
13 & 15 & 17 & 19 & 21 & 23 \\
\end{bmatrix}
\]  \hspace{1cm} (19)

\[
Y = \begin{bmatrix}
Y_1 \\
Y_2 \\
\vdots \\
Y_n \\
\end{bmatrix} = \begin{bmatrix}
1.279 & 1.13 & 1.012 & 0.916 & 0.837 & 0.769 \\
0.967 & 0.982 & 0.997 & 1.012 & 1.028 & 1.043 \\
0.58 & 0.723 & 0.867 & 1.012 & 1.16 & 1.311 \\
1.055 & 1.037 & 1.023 & 1.012 & 1.004 & 0.996 \\
\end{bmatrix}
\]  \hspace{1cm} (20)

The above matrix is interval relative valued by formula (3), and the difference sequence matrix is formed by formula (6). The grey correlation coefficient matrix can be obtained. It is dimensionless by formula (13), from which the ideal samples $B^+$ and $B^-$ are selected. The distance from each sample point to the reference sample point is calculated by the Euclidean distance formula (16), and each index sample point is calculated by formula (17) To the relative approach degree of the optimal
sample point, the vector value of the correlation degree weight is obtained by formula (18). Finally, using equation (11), the correlation degree between each influencing factor and landslide stability is $\gamma_i = [0.897 \ 0.663 \ 0.993 \ 0.654]^T$. According to the sequence of correlation degree, the order of influence on the stability of a loess landslide is as follows: internal friction angle of sliding zone soil, horizontal seismic acceleration coefficient, cohesion of sliding zone soil, landslide weight degree. That is to say, the internal friction and horizontal seismic acceleration coefficient have the greatest influence on the stability of a loess landslide.

5. Conclusion
In view of the defects of the traditional grey correlation method, the distance analysis method is introduced to improve the calculation of the correlation degree, and the correlation degree of each influencing factor of the stability of a loess landslide is calculated based on it. The calculation result is $\gamma_i = [0.897 \ 0.663 \ 0.993 \ 0.654]^T$, that is, the order of magnitude is: friction angle in the sliding zone soil, horizontal seismic acceleration coefficient, cohesion of the sliding zone soil, and the weight of the sliding body.

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