Study on Open-pit Mine Slope Stability Based on Improved TOPSIS Method

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Abstract. In order to evaluate the slope instability risk of open-pit mine more accurately, this paper establishes a slope instability risk evaluation model based on Improved TOPSIS method according to the hierarchical holographic modeling method and entropy method. In this paper, the hierarchical holographic modeling method is used to establish the evaluation index system of open-pit slope stability, and 11 main indexes which have great influence on the stability are selected. The weights of 11 main indexes are calculated by using entropy method, and then applied to TOPSIS method. Finally, the positive and ideal solution distances of 5 typical open-pit slopes are calculated and the destabilization risk of 5 open-pit slopes is reasonably evaluated. The evaluation results were compared with those of other evaluation models to verify their rationality. The results show that the slope evaluation method based on improved TOPSIS can effectively evaluate the slope stability, which provides a new method for determining the high risk slope and effectively rating the slope risk.

1. Introduction
The production safety of open-pit mine is closely related to the stability of goaf slope. For open-pit mine slope with complex physical parameters and external disturbance factors, selecting the indicators with significant influence and make a scientific evaluation of the slope is an important subject. Many scholars have made some progress in the study of slope evaluation methods. The abrupt theory [1], genetic algorithm [2], fuzzy comprehensive evaluation method [3], extension theory [4], neural network [5] and other methods have been widely used in slope stability evaluation. However, all kinds of indexes affecting the slope stability are coupled with each other and have different effects on the slope. So it is difficult to determine reasonable indexes and weights from the wide range of factors affecting the slope stability only by relying on the evaluation method, and effective evaluation results are hardly to be obtained [6].

In this paper, the entropy method and the hierarchical holographic modeling method are introduced into the comprehensive evaluation method (TOPSIS method) to establish a model of slope stability evaluation. The advantages of hierarchical holographic modeling method, entropy method and TOPSIS method in index selection, weight calculation and model evaluation are converged into this model. So it can quickly determine the main indexes affecting the stability of open-pit mine slope and calculate the weight, obtain the close distance between the slope and the positive ideal solution, and evaluate the risk
degree of slope instability. It has been proved that the model is feasible and accurate, and can be widely used in the evaluation of open-pit mine slope.

2. An improved TOPSIS method for open-pit mine slope evaluation

2.1. The construction of multi-level stability evaluation system

There are many factors affecting open-pit mine slope. Some of them are interrelated, and don’t have clear quantitative index. In order to evaluate the slope stability of open-pit mine effectively, a set of reasonable and effective evaluation index system need to be established firstly. Hierarchical holographic modeling method is a method that can divide the factors affecting the open-pit slope into different levels and show the characteristics and relationships of various influencing indexes. The process of establishing the open-pit mine slope evaluation system by hierarchical holographic modeling method is as follows:

(1) Based on the norms and field experience, different main perspectives of open-pit mine slope evaluation were determined, and each perspective was determined as a subsystem. Subsystems are not quantitative indicators, each subsystem is independent of each other, and the internal correlation among them is not significant.

(2) Determine the quasi components in each subsystem, and the components are the indicators to participate in the evaluation. Each part is quantitative, if not, the expert scoring method is used to give the score.

(3) The rationality of the quasi-component setting of each subsystem was investigated from the aspects of component compatibility and accessibility, etc. The final subsystem components were determined after adjustment, and the evaluation indexes of the open-pit mine slope was displayed in the form of a chart.

2.2. Weighting of stability evaluation indexes

In order to determine the importance of each index, it is necessary to reasonably assign weight to the index after determining the m item evaluation index of the open-pit mine slope. Entropy value method is a weight calculation method that can be properly adjusted according to the state of different indicators [7], so as to obtain a weight calculation method that is more in line with the objective situation. It can effectively reduce the disadvantage of "weight imbalance" in the calculation method of constant weight, and more truly and completely reflect the engineering practice. Thus it has been widely used in engineering risk assessment, especially in slope stability evaluation [8]. At the same time, the entropy method can directly determine the weight value of the index according to the information of the sample data itself, which has higher credibility. For n samples participating in the evaluation, m appropriate indexes are selected for evaluation and weighting. The weight calculation process of each index is as follows:

(1) Standardization of indicators

Since the dimension and value range of each index are not exactly the same, the absolute value of each index should be converted into relative value according to Equation (1) before calculation.

\[ r_j = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \]  (1)

Where \(x_{ij}\) represents the value of the number j index of the number i sample (i=1,…, n; j=1,…,m)

(2) Calculate the entropy value of the number j index

The degree of dispersion of different indexes varies greatly. The entropy value \(e_j\) is used to represent the degree of dispersion of selected indexes. The higher the entropy value is, the greater the dispersion of indexes will be.

\[ e_j = -k \sum_{i=1}^{n} r_{ij} \ln(r_{ij}) \]  (2)

where k=1/ln(n)>0. \(e_j\)≥0
(3) Calculate the information utility value
The information utility value is also called the information entropy redundancy and is denoted by $l_j$. It reflects the reliability of information, which is numerically equal to the difference between the information entropy $e_j$ of the evaluation index and 1. The larger the information utility value $l_j$ is, the more meaningful the index will be in the process of investigating the evaluation object, and the larger the corresponding weight value will be in the subsequent evaluation.
$$l_j = 1 - e_j \quad (3)$$

(4) Calculate the weight of each index
By comparing the information utility value of the m indexes, the final weight $w_j$ of the index in the evaluation system was calculated.
$$w_j = \frac{l_j}{\sum_{j=1}^{m} l_j} \quad (4)$$

2.3. Stability evaluation
After determining the weight value of the m indexes affecting the open-pit slope, TOPSIS method (the distance between good and bad solutions method) is introduced into to make the final evaluation. TOPSIS is a method to determine the positive and negative ideal solutions of the evaluation target, and then calculate and compare the distance between the evaluation object and the positive and negative ideal solutions, so as to make a reasonable evaluation of the evaluation object [9]. Compared with the fuzzy comprehensive evaluation method and the extension goodness method, the TOPSIS method can make full use of the original data information of the evaluation object to calculate the degree of difference between the evaluation object and the ideal state. It has the advantages of simple calculation, strong objectivity and accurate results, and has been effectively applied in the evaluation of open-pit mine slope stability. After obtaining the statistical value of each index and the weight of each index of the evaluation object, the positive and negative ideal solution distance of the evaluation object is calculated through the following process:

(1) Construction of the initial matrix
The open-pit mine slope set to be evaluated is $P$, $a_{ij}$ represents the number $j$ evaluation index of the number $i$ slope, then $P$ can be expressed as
$$P = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix} \quad i \in [1, m], j \in [1, n]$$

(2) Construction of standardized evaluation matrix
Since there are dimensional and unit differences among the indicators, the uncommensurability needs to be eliminated, and the vector normalization calculation of $a_{ij}$ is carried out to get $b_{ij}$.
$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{m} a_{ij}} \quad (5)$$

Then, the weighted values $w_{ij}$ and $b_{ij}$ obtained by the entropy method are multiplied to obtain the standardized evaluation matrix $C$:
$$C = (c_{ij})_{m \times n} = \begin{bmatrix} w_1 b_{11} & w_1 b_{12} & \cdots & w_1 b_{1n} \\ w_2 b_{21} & w_2 b_{22} & \cdots & w_2 b_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_n b_{n1} & w_n b_{n2} & \cdots & w_n b_{nn} \end{bmatrix} \quad (6)$$

(3) Calculation of the closeness degree between the evaluation object and the ideal solution:
\[
\begin{align*}
C^+ &= \{(\max c_j | j \in J_1), (\min c_j | j \in J_2)\} \\
C^- &= \{(\min c_j | j \in J_1), (\max c_j | j \in J_2)\}
\end{align*}
\] (7)

Where, \(C^+\) is the positive ideal solution, that is, the ideal standard of the evaluation object; \(C^-\) is the negative ideal solution, that is, the least ideal standard of the evaluation object; \(J_1\) is a benefit index. The larger the index value is, the better the evaluation object is. \(J_2\) is a cost-type index. The larger the index value is, the worse the evaluation object is.

The calculation formula of the distance between each evaluation object and the ideal solution is as follows:
\[
\begin{align*}
d_i^+ &= \sqrt{\sum_{j=1}^{n} (c_{ij} - c^+)_j^2} \\
d_i^- &= \sqrt{\sum_{j=1}^{n} (c_{ij} - c^-)_j^2}
\end{align*}
\] (8)

Where, \(d_i^+\) is called the positive ideal solution distance, which refers to the distance between the realistic state and the ideal state of the evaluation object; \(d_i^-\) is called the negative ideal solution distance, which refers to the distance between the evaluation object and the least ideal state; \(c_{ij}^+\) is the number \(j\) member of the positive ideal solution \(C^+\), and \(c_{ij}^-\) is the \(j\) member of the negative ideal solution \(C^-\). The larger the \(d_i^+\) is, the closer the evaluation object is to the optimal state.

3. Application instance

In order to verify the accuracy of the evaluation model of open-pit mine slope based on the improved TOPSIS method, this chapter uses this method to calculate three typical slopes of an open-pit mine in Hunan Province (S1-S3) and two typical slopes of an open-pit mine in Jiangxi Province (S4-S5). The physical and mechanical parameters, the structural plane characteristics and slope conditions are determined according to the field survey data. Refer to relevant specifications for rainfall and basic ground motion data of the site. The evaluation results will compare with the calculation results of grey correlation method and BP neural network method to verify the accuracy of the evaluation results.

3.1. Multi-level stability evaluation system of open-pit mine slope

The indexes affecting the slope stability of open-pit mine mainly include physical and mechanical parameters of rock mass, structural plane characteristics, slope geometry characteristics, and possible disturbance [10]. Based on the hierarchical holographic modeling method, the stability evaluation system is established, and the four aspects are taken as the subsystems of the multi-level stability evaluation system of open-pit mine slope. In the subsystem of physical and mechanical parameters of rock mass, the difficulty of obtaining indexes and the research results of other scholars are considered, four components of saturated uniaxial compressive strength \(Rc\) (I1), deformation modulus \(E_0\) (I2), cohesion \(c\) (I3) and internal friction Angle \(\varphi\) (I4) were selected as evaluation indexes. In the subsystem of structural plane characteristics, rock integrity index \(KV\) (I5), cohesion of main structural plane \(c_0\) (I6) and structural plane friction Angle \(\varphi_0\) (I7) of main structural plane are selected as evaluation indexes. In the subsystem of slope geometric characteristics, the slope height \(H\) (I8) and slope Angle \(\alpha\) (I9) are selected as evaluation indexes. In terms of possible external disturbances, the two components of the maximum daily rainfall \(h\) (I10) and the basic ground motion peak acceleration \(a\) (I11) of the site are selected as evaluation indicators. The final multi-level stability evaluation system of open-pit mine slope is shown in Fig. 1.
The multi-level stability evaluation system of open-pit slope is established by hierarchical holographic modeling method. Referring to relevant industry standards and other scholars’ work [11-13], the slope stability of open pit mine is divided into very stable (level I), stable (level II), basically stable (level III), unstable (level IV) and extremely unstable (level V). The quantitative interval of each level index is shown in Table 1.

Table 1. Classification standards of indicators.

| Level Stability | I1/MPa | I2/MPa | I3/MPa | I4/° | I5 | I6/MPa | I7/° | I8/m | I9/° | I10/mm | I11 |
|-----------------|--------|--------|--------|------|----|--------|------|------|------|--------|-----|
| Level I         | >60    | >33    | >2.1   | >0.75| >0.22| <37    | <8   | <15  | <20  | <0.1g  |     |
| Level II        | 30-60  | 16-33  | 1.5-2.1| 0.55-0.75| 0.12-0.22| 29-37 | 8-15 | 15-30| 20-40| 0.1g-0.2g|     |
| Level III       | 15-30  | 6-16   | 0.7-1.5| 39-50 | 0.35-0.55| 0.08-0.12| 19-29 | 15-30| 30-45| 40-60   | 0.2g-0.3g|
| Level IV        | 5-15   | 1.3-6  | 0.2-0.7| 27-39 | 0.15-0.35| 0.05-0.08| 13-19 | 30-60| 45-60| 60-100  | 0.3g-0.4g|
| Level V         | ≤5     | ≤1.3   | ≤0.2   | ≤27   | ≤0.15 | ≤0.05  | ≤13  | ≥60  | ≥60  | ≥100   | ≥0.4g|

3.2. Weighting of stability evaluation indexes

According to equation (1), the absolute values of 11 indexes are transformed into relative values, and the indexes are standardized to obtain the standardized matrix $x_i$:

$$x_i = \begin{bmatrix}
0.2583 & 0.2179 & 0.3021 & 0.2377 & 0.2724 & 0.2658 & 0.2239 & 0.2201 & 0.1880 & 0.1654 & 0.1429 \\
0.2458 & 0.1868 & 0.2183 & 0.2048 & 0.2642 & 0.2278 & 0.2612 & 0.2075 & 0.1960 & 0.1654 & 0.1429 \\
0.1417 & 0.1861 & 0.1493 & 0.1508 & 0.1545 & 0.2658 & 0.2642 & 0.2152 & 0.2440 & 0.1654 & 0.1429 \\
0.2250 & 0.2200 & 0.1822 & 0.2148 & 0.2114 & 0.1013 & 0.2164 & 0.2956 & 0.1520 & 0.2519 & 0.2857 \\
0.1292 & 0.1892 & 0.1482 & 0.1920 & 0.0976 & 0.1392 & 0.1343 & 0.1195 & 0.2200 & 0.2519 & 0.2857 
\end{bmatrix}$$

Entropy value $E_j$, information utility value $l_j$ and weight value $w_j$ of the number $j$ index affecting slope stability are calculated according to Equations (2), (3) and (4). The calculated results are shown in Table 2.

Table 2. Weight value of each indicator.

| Evaluating Indicator | Physical and mechanical parameters of rock mass | Structural plane characteristics | Slope geometry characteristics | Disturbance |
|----------------------|-----------------------------------------------|---------------------------------|-------------------------------|-------------|
| $e_j$                | 0.9764                                       | 0.9981                          | 0.9760                        | 0.9933      | 0.9631 | 0.9617 | 0.9837 | 0.9721    | 0.9924 | 0.9864 | 0.9630 |
| $l_j$                | 0.0236                                       | 0.0019                          | 0.0240                        | 0.0067      | 0.0369 | 0.0383 | 0.0163 | 0.0279    | 0.0076 | 0.0136 | 0.0370 |
| $w_j$                | 0.1011                                       | 0.0079                          | 0.1025                        | 0.0285      | 0.1581 | 0.1638 | 0.0696 | 0.1194    | 0.0324 | 0.0583 | 0.1585 |
Compared with the index weight $w_j$, the cohesion of the main structural plane $c_0$, the basic ground motion peak acceleration $a$ and the rock integrity coefficient $K_v$ have great influence on the slope stability. The deformation modulus $E_0$ and internal friction angle of rock have little influence on slope stability.

3.3. Calculation of the positive ideal solution distance of each evaluation object

(1) The field data of five slopes are substituted into TOPSIS model to construct the standardized matrix. By calculating the distance between each mine slope and the positive rational solution, the risk degree of slope instability in five open-pit mines is obtained. The specific evaluation process is as follows: The initial matrix $P$ is constructed, in which the first five behaviors are based on the slope field data obtained from the investigation data and relevant specifications, and the last four behaviors are risk interval critical values.

$$
P = \begin{array}{cccccccccc}
62 & 63.5 & 85.4 & 52 & 0.67 & 0.21 & 30 & 35 & 47 & 67 & 0.05 \\
59 & 54.0 & 61.7 & 45 & 0.65 & 0.18 & 35 & 33 & 49 & 67 & 0.05 \\
34 & 53.8 & 42.2 & 33 & 0.38 & 0.21 & 22 & 21 & 61 & 67 & 0.05 \\
54 & 63.6 & 51.5 & 47 & 0.52 & 0.08 & 29 & 47 & 38 & 102 & 0.10 \\
31 & 54.7 & 41.9 & 42 & 0.64 & 0.24 & 11 & 18 & 19 & 55 & 102 & 0.10 \\
60 & 33.0 & 21.0 & 60 & 0.75 & 0.22 & 37 & 8 & 15 & 20 & 0.10 \\
30 & 16.0 & 15.0 & 50 & 0.55 & 0.12 & 29 & 15 & 30 & 40 & 0.20 \\
15 & 6.00 & 0.70 & 39 & 0.35 & 0.08 & 19 & 30 & 45 & 60 & 0.30 \\
5 & 1.30 & 0.20 & 27 & 0.15 & 0.05 & 13 & 60 & 60 & 100 & 0.40 \\
\end{array}
$$

The benefit type indexes include saturated compressive strength ($I_1$), deformation modulus ($I_2$), cohesion ($I_3$), internal friction angle ($I_4$), integrity coefficient ($I_5$), cohesion of main structural plane ($I_6$) and internal friction angle ($I_7$). The larger these values are, the more conducive to slope stability. The cost index includes slope height ($I_8$), slope angle ($I_9$), daily maximum rainfall ($I_{10}$) and basic ground motion peak acceleration ($I_{11}$). The smaller the value is, the better the slope stability is. According to equation (7), the positive and negative ideal solutions are calculated as follows:

$$
\begin{align*}
C^+ &= \begin{pmatrix}
0.0179 & 0.0006 & 0.0267 & 0.0038 & 0.0249 & 0.0273 & 0.0090 & 0.0154 & 0.0038 & 0.0063 & 0.0059 \\
0.0170 & 0.0005 & 0.0193 & 0.0032 & 0.0241 & 0.0234 & 0.0105 & 0.0145 & 0.0040 & 0.0063 & 0.0059 \\
0.0098 & 0.0005 & 0.0132 & 0.0024 & 0.0141 & 0.0273 & 0.0066 & 0.0110 & 0.0049 & 0.0063 & 0.0059 \\
0.0156 & 0.0006 & 0.0161 & 0.0034 & 0.0193 & 0.0104 & 0.0087 & 0.0206 & 0.0031 & 0.0095 & 0.0117 \\
0.0090 & 0.0005 & 0.0131 & 0.0030 & 0.0089 & 0.0143 & 0.0054 & 0.0083 & 0.0045 & 0.0095 & 0.0117 \\
0.0173 & 0.0031 & 0.0066 & 0.0043 & 0.0278 & 0.0286 & 0.0111 & 0.0035 & 0.0012 & 0.0019 & 0.0117 \\
0.0087 & 0.0015 & 0.0047 & 0.0036 & 0.0204 & 0.0156 & 0.0087 & 0.0066 & 0.0024 & 0.0037 & 0.0235 \\
0.0043 & 0.0006 & 0.0022 & 0.0028 & 0.0130 & 0.0104 & 0.0057 & 0.0132 & 0.0036 & 0.0056 & 0.0352 \\
0.0014 & 0.0001 & 0.0006 & 0.0019 & 0.0056 & 0.0065 & 0.0039 & 0.0263 & 0.0049 & 0.0093 & 0.0470 
\end{pmatrix} \\
C^- &= \begin{pmatrix}
0.0017 & 0.0031 & 0.0027 & 0.0043 & 0.0278 & 0.0286 & 0.0111 & 0.0035 & 0.0012 & 0.0019 & 0.0059 \\
0.0014 & 0.0001 & 0.0006 & 0.0020 & 0.0058 & 0.0065 & 0.0039 & 0.0263 & 0.0049 & 0.0095 & 0.0470 
\end{pmatrix}
\end{align*}
$$

According to formula (8), the ideal solution distance of S1-S5 and the interval of slope of each level are calculated. The results are shown in Table 3.
### Table 3. Ideal solution distance and safety factor of mine slope.

| Evaluation object | Ideal solution distance(Improved TOPSIS) | Evaluation results(Improved TOPSIS) | Ideal solution distance(TOPSIS) | Evaluation results(TOPSIS) |
|-------------------|------------------------------------------|-----------------------------------|--------------------------------|-----------------------------|
| level I           | <0.00587                                 | <0.20006                          |                                |                             |
| level II          | 0.00587-0.02354                           | 0.20006-0.34653                   |                                |                             |
| level III         | 0.02354-0.03943                           | 0.34653-0.50620                   |                                |                             |
| level IV          | 0.03943-0.05757                           | 0.50620-0.64670                   |                                |                             |
| level V           | ≥0.05757                                 | ≥0.64670                          |                                |                             |
| S₁                | 0.01346                                  | level II                          | 0.34904                        | level III                   |
| S₂                | 0.01373                                  | level II                          | 0.36696                        | level III                   |
| S₃                | 0.01730                                  | level II                          | 0.40999                        | level III                   |
| S₄                | 0.02827                                  | level III                         | 0.41104                        | level III                   |
| S₅                | 0.02687                                  | level III                         | 0.43682                        | level III                   |

### 3.4. Validation

The validity of the evaluation model is judged by comparing the conclusions of different methods. The extension theory method, catastrophe theory method and fuzzy comprehensive evaluation method are used to evaluate S₁-S₅. The evaluation results are shown in Table 4. In S₁-S₄, the results of the improved TOPSIS method are consistent with those of other methods. In S₅, the evaluation results of improved TOPSIS method, extension theory method and catastrophe theory method are level II (stable), while the evaluation results of fuzzy comprehensive evaluation method are level I (very stable). Therefore, the results of TOPSIS are basically consistent with those of other methods. The results of TOPSIS method for S₁-S₃ are three levels, which are different from other methods. It is proved that the level holographic modeling method and entropy method can increase the accuracy of the evaluation results.

### Table 4. Stability rating of mine slope.

| Evaluation object | Improved TOPSIS | TOPSIS | Extension theory method | Catastrophe theory method | Fuzzy comprehensive evaluation method |
|-------------------|-----------------|--------|-------------------------|---------------------------|---------------------------------------|
| S₁                | level II        | level III | level II                | level II                  | level I                               |
| S₂                | level II        | level III | level II                | level II                  | level II                               |
| S₃                | level II        | level III | level II                | level II                  | level II                               |
| S₄                | level III       | level III | level III               | level III                 | level III                              |
| S₅                | level III       | level III | level III               | level III                 | level III                              |

### 4. Conclusion

1. By introducing the hierarchical holographic modeling method and entropy method into the slope stability evaluation method of open-pit mine, the evaluation system of open-pit mine slope can be established, and the main indexes and weight values affecting the slope stability of open-pit mine can be determined. The weight results show that the cohesion of the main structural plane, the basic ground motion peak acceleration of the site and the rock integrity coefficient have a significant impact on the slope stability, while the deformation modulus of rock mass and the internal friction angle of rock have a small impact on the slope stability.

2. The improved TOPSIS method is used to evaluate the stability of five open pit slopes, such as S₁-S₅. The slope S₁-S₃ is level II (stable), and the slope S₄-S₅ is level III (basically stable). Compared with TOPSIS, the results of the improved TOPSIS are closer to those of extension theory, catastrophe theory and fuzzy comprehensive evaluation method. The application of hierarchical holographic modeling method and entropy method in TOPSIS method can effectively improve the reliability of evaluation results of open pit slope.

3. The improved TOPSIS slope stability evaluation model can effectively determine the open-pit mine slope stability evaluation index system. The calculation process of this method is simple and direct, and the results are objective and reliable, which can make a more scientific, comprehensive and accurate
judgment for the slope stability of open-pit mine. The model can also be widely used in other multi index evaluation objects.

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