Stability evaluation of transmission tower above the goaf by fuzzy comprehensive evaluation method and analytic hierarchy process

Wenyan Qi\textsuperscript{1,3}, Fang Ye\textsuperscript{1}, Wenyue Qi\textsuperscript{2}, Tian Li\textsuperscript{1}, Sensen Guan\textsuperscript{1}, Siwei Fu\textsuperscript{1}, Xunda Zhang\textsuperscript{1} and Shaoyu Chen\textsuperscript{1}

\textsuperscript{1} Tianjin Electric Power Corporation Electric Power Research Institute
\textsuperscript{2} Yanshan University
\textsuperscript{3} E-mail: 1dqwenyan@126.com

Abstract. Combination of the load-bearing conditions, the tower shape and service time, and the geological and basic conditions of the service environment of the tower, various factors that influence the stability of the towering tower near goaf were classified by using fuzzy comprehensive evaluation method and AHP, and the influence factor model was established. The impact factors were evaluated from low to high, the influence of the geological and basic conditions of the service environment is maximal, and determined the approximate rock roadway is stable and no measures need to take to improve the stability of the tower.

1. Introduction
The distribution of coal resources is very wide, and the large and small mines are distributed all over the country. Large-scale goaf have been formed in many coal mining areas, resulting in more than 700000 hectares of land subsidence area. High-voltage transmission lines inevitably cross the old coal mine goaf with the development of social economy and the improvement of power grid construction [1]. As time goes on, the residual deformation of the overburden in the goaf may have a great impact on the high-voltage transmission line, which result in the foundation settlement, cracking, tower body tilting, tower toppling, line breaking, threatening the operation of the line, causing a large-scale power failure and even threatening the life and property safety of the people. How to accurately evaluate the stability of the tower above the goaf is the premise of the safe operation of the transmission line.

Recently, some research results have been achieved in coal mining under the transmission tower and the stability of the tower above the goaf [2-3]. Xia et.al studied the interaction mechanism of the foundation, strip foundation and frame structure in the mining area, and the law of the influence of the surface deformation on the foundation reaction force and foundation internal force [4]. Wu et.al analyzed the "activation" deformation source of the long wall old goaf, and clarified the general method of evaluating the stability of the foundation in the goaf and the suitability of erecting the tower are introduced [5]. Guo et.al expounded that the tower of the high-voltage transmission line is not a single isolated structure, but a spatial structure system composed of the foundation, foundation, tower structure and conductor, and its deformation law is different from that of the general high-rise buildings [6-7]. The problems related to the Subsidence Reduction and protection of multi-seam mining under the high-voltage power supply line are researched by Song et.al with in-situ rock movement observation and the comprehensive research method of numerical simulation [8]. However,
the existing researches mainly focus on the stability control and mining method design of high-rise tower under the influence of mining, and hardly any research is carried on the evaluation of the stability of the tower by the residual deformation of the goaf.

The performance of the tower will decline especially over the goaf with the extension of the service time, as well as the foundation will subside or collapse, resulting in the tower tilt or even collapse. Therefore, it is an urgent practical problem to reasonably evaluate the stability of the high-rise tower over the goaf. In this paper, the influence of the residual deformation of the goaf on the stability of the high-rise tower is analyzed, a comprehensive evaluation method considering environmental factors, tower performance, foundation conditions, goaf deformation and other factors is put forward, the key factors affecting its stable operation is illustrated, and a reasonable evaluation of the stability of the high-rise tower can be made, which provides theoretical support for stable operation evaluation of transmission line tower above the goaf.

2. Influence of overburden deformation on transmission tower above the goal

The overlying rock and the surface of the goaf will enter a relatively stable state by the influence of the deformation of the overlying rock of the goaf after a long time of natural compaction, but the remaining underground cavities and separation caused by mining will still exist for a long time. It is equivalent to the broken rock of the goaf and the secondary equilibrium structure of overburden is more easily broken when additional load is applied to the layer as the transmission tower is built above the goaf. The relative stability of the overlying strata and the surface of the goaf will be changed, which will lead to the separation of the strata and the collapse of the surface, resulting in inclination or collapse of the tower above the goaf. Figure 1 shows the state of the goaf and overlying fractured rock mass.

![Figure 1. The state of the goaf and overlying cracked rock mass.](image)

3. Establishment of stability evaluation index of high tower in old goaf

3.1. Introduction of the engineering

The coal mine discovered has been mined by long-wall mining in 1997, with a mining depth of 215-272 m. The lithology of the goaf is mainly composed of quartz sandstone, mud-stone and sandy mud-stone. A new transmission line passed through the goaf in 2005. N3 tower was built in the direction of the downhill of the mining face with a plane distance of 150 m. The type of N3 tower is self-supporting angle steel tower with a height of 47.5 m. The two adjacent towers are N2 and N4, the span between N2 and N3 is 533 m, and the span between N3 and N4 is 571 m. The location relationship is shown in Figure 2.

3.2. Evaluation method

The fuzzy comprehensive evaluation method [9-10] is used to build the stability evaluation index system of high-rise iron tower above the goaf, and then the specific evaluation indexes of each classification are determined. The stability evaluation set of high-rise iron tower on the goaf is established, and the fuzzy evaluation membership matrix relative to the evaluation set is established by
expert scoring. The Analytic hierarchy process (AHP) method \[11\] is used forming a \( n \times n \) judgment matrix, the relative importance of each factor is expressed by a number between 1 and 9, determining the weight of each evaluation index, and calculating the maximum eigenvalue of the judgment matrix, so as to test the consistency of the judgment matrix. The result is considered reliable, when the consistency index is less than 0.1 \[12\]. The result matrix of fuzzy comprehensive evaluation is obtained by combining it with the membership matrix of fuzzy evaluation, and the rational decision is made.

\[\text{Figure 2. The location of the N3 tower.}\]

\subsection*{3.3. Selection of evaluation indexes}

The main factors affecting the stability operation of the iron tower include the load-bearing condition of the iron tower, the service time of the iron tower, the corrosion condition of the iron tower, the firmness degree of the foundation and the underground goaf condition, and so on. According to the classification of the above factors, the stability evaluation indexes of the tower above the goaf can be divided into three categories: the load-bearing condition, the shape and service time of the iron tower, and the geological and basic conditions. The stability evaluation index system of the transmission tower above the goaf is constructed by according to the analysis of various indexes, as shown in Figure 3.

\[\text{Figure 3. The stability evaluation model of transmission tower above the goaf.}\]
3.4. Determination of evaluation set and fuzzy evaluation matrix

Figure 3 shows that the evaluation index set is divided into two layers:

1) The total objective factor set \( U \) can be expressed as \( U = (M_1, M_2, M_3) \).

2) Sub objective factor sets \( M_1, M_2 \) and \( M_3 \), each containing 4 evaluation factors, can be expressed as:

\[
M_1 = (N_{11}, N_{12}, N_{13}, N_{14}) \\
M_2 = (N_{21}, N_{22}, N_{23}, N_{24}) \\
M_3 = (N_{31}, N_{32}, N_{33}, N_{34})
\]

The evaluation set is the evaluation set of each evaluation index, which is a language level description of each level of evaluation index. If the evaluation set is \( V \) and \( M \) evaluation grades are included, the evaluation set of evaluation grades is \( V = (V_1, V_2, V_m) \). The evaluation of the fuzzy comprehensive evaluation model studied in the paper is divided into four levels, and the specific evaluation set is: \( V = \) (very stable, stable, unstable, very unstable).

According to the evaluation set, each index affecting the stability of the transmission iron tower above the goaf is evaluated by the way of expert scoring. The fuzzy evaluation matrix is constructed based on the comprehensive evaluation factor set and the evaluation set after the membership degree is calculated. The fuzzy evaluation matrix of the sub target factor sets \( M_1, M_2 \) and \( M_3 \) for the evaluation set \( V \) are shown as follows:

\[
A_1 = \begin{bmatrix}
1 & 0 & 0 & 0 \\
3 & 1 & 0 & 0 \\
4 & 4 & 0 & 0 \\
1 & 1 & 1 & 0 \\
4 & 2 & 1 & 0 \\
6 & 3 & 6 & 0
\end{bmatrix} \\
A_2 = \begin{bmatrix}
1 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 1 & 1 & 0 \\
6 & 2 & 3 & 0 \\
0 & 3 & 1 & 0 \\
4 & 4 & 0 & 0
\end{bmatrix} \\
A_3 = \begin{bmatrix}
1 & 1 & 1 & 0 \\
4 & 2 & 4 & 0 \\
0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 \\
1 & 1 & 2 & 0 \\
6 & 6 & 3 & 0
\end{bmatrix}
\]

4. Index weight determination

4.1. Construct the contrast matrix

The importance of the parallel elements in the same index layer relative to a factor in the previous layer is described by the quantitative relative weight \( a_{ij} \) using analytic hierarchy process. If there are \( n \) elements participating in the comparison, the pairwise comparison matrix is constructed as follows:

\[
A = (a_{ij})_{n \times n}
\]

Table 1 shows the rules for each element in pairwise comparison matrix.

| Number | Rules | 
|--------|-------|
| 1      | According to the criterion of a certain element in the above level, the element in this level is as important as element j |
| 3      | Compared with element j, element i of this level is slightly more important than element j |
| 5      | Compared with element j, element i of this level is more important than element j |
| 7      | Compared with element j, element i of this level is much more important than element j |
| 9      | Compared with element j, element i of this level is absolutely more important than element j |
| 2, 4, 6, 8 | Intermediate value of the above judgment |

Reciprocal

If the importance ratio of element i to element j is \( a_{ij} \), the importance ratio of element j to element i is \( a_{ji} = \frac{1}{a_{ij}} \).

According to the importance of each criterion level in the target level, the corresponding scores are given by the way of expert scoring, and the scoring is conducted according to the 10-point system. The
higher the score is, the more important the indicator is. There are 10 scoring experts, including mining engineering, geotechnical mechanics, power construction and planning, power grid technical supervision, and equipment status evaluation. The average score of each expert is taken as the comprehensive evaluation value of the importance of this index. The scoring of criterion layer is shown in Table 2.

| Experts | M1 | M2 | M3 |
|---------|----|----|----|
| 1       | 8  | 9  | 9  |
| 2       | 8  | 10 | 9  |
| 3       | 8  | 9  | 8  |
| 4       | 7  | 9  | 8  |
| 5       | 8  | 9  | 8  |
| 6       | 7  | 8  | 8  |
| 7       | 8  | 10 | 8  |
| 8       | 8  | 9  | 8  |
| 9       | 8  | 9  | 8  |
| 10      | 8  | 8  | 7  |
| Average | 7.800 | 9.000 | 8.100 |

The judgment matrix U of stability evaluation index system of transmission iron tower above the goaf shows as follow:

\[
U = \begin{pmatrix}
1 & 1 & 1 \\
\frac{1}{5} & \frac{1}{3} & 3 \\
\frac{1}{5} & \frac{1}{3} & 1
\end{pmatrix}
\]

In the same way, each factor of bearing load, geological and foundation conditions, tower shape and service time is scored, and the contrast matrix N1, N2 and N3 are obtained.

\[
N_1 = \begin{pmatrix}
1 & \frac{1}{3} & \frac{1}{5} \\
\frac{1}{3} & 1 & \frac{1}{5} \\
\frac{1}{5} & \frac{1}{3} & 1
\end{pmatrix}
\]

\[
N_2 = \begin{pmatrix}
1 & 2 & \frac{1}{3} \\
\frac{2}{3} & 1 & \frac{1}{5} \\
\frac{3}{5} & \frac{1}{2} & 1
\end{pmatrix}
\]

\[
N_3 = \begin{pmatrix}
1 & 5 & \frac{1}{3} \\
\frac{1}{5} & 1 & \frac{2}{3} \\
\frac{1}{5} & \frac{2}{3} & 1
\end{pmatrix}
\]

4.2. Consistency test
If the matrix is a completely consistent pairwise comparison matrix, there is \(a_{ij}a_{jk}=1, 1 \leq i, j, k \leq n\), but the constructed pairwise comparison matrix cannot be strictly consistent, so as long as the pairwise comparison matrix has a condition of consistency. The random consistency ratio CR of the paired comparison matrix is calculated by Formula (1).

\[
CR = \frac{CI}{RI}
\]
CI represents the degree of inconsistency of a pair comparison matrix, and RI is the standard to test the consistency of the pair comparison matrix and is only related to N, $\lambda_{\text{max}}(A)$ is the eigenvalue with the largest absolute value of matrix A, and N is the order of paired comparison matrix in the formulas. The pairwise comparison matrix is considered to have satisfactory consistency when CR < 0.1, and if, the pairwise comparison matrix is considered to have satisfactory consistency when CR ≥ 0.1. Table 3 shows the value of RI.

**Table 3. The value of RI.**

| n  | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RI | 0.00| 0.00| 0.58| 0.90| 1.12| 1.24| 1.32| 1.41| 1.45|

4.3. **Calculation of the weight value**

The above process is applied to the stability evaluation model of the transmission tower above the goaf, the weight vector of the pairwise comparison matrix of each layer is calculated, and the consistency results are as follows:

1) Calculation results of paired comparison matrix U:
   
   $\lambda_{\text{max}}=3.00344$, CR=0.0025, feature vector $Q=(0.1061, 0.6334, 0.2605)^T$

2) Calculation results of paired comparison matrix N1:
   
   $\lambda_{\text{max}}=4.0037$, CR=0.0010, feature vector $Q_1=(0.0702, 0.1923, 0.4060, 0.3315)^T$

3) Calculation results of paired comparison matrix N2:
   
   $\lambda_{\text{max}}=4.0033$, CR=0.0012, feature vector $Q_2=(0.0810, 0.1280, 0.4351, 0.3559)^T$

4) Calculation results of paired comparison matrix N3:
   
   $\lambda_{\text{max}}=4.0806$, CR=0.0299, feature vector $Q_3=(0.2444, 0.1354, 0.1113, 0.5089)^T$

According to the above calculation results, each pair of comparison matrix in this model meets CR < 0.1, so it can be judged that it conforms to the consistency principle and the weight vector obtained is effective.

5. **Calculation results of objective evaluation**

The fuzzy evaluation matrix and weight vector calculated above are combined to evaluate the middle layer and then the target layer.

5.1. **Evaluation criterion layer**

1) Evaluation of sub objective factor set $A_1$:
   
   $P_1 = Q_1^T \cdot A_1 = (0.3712, 0.4712, 0.1568, 0)$

2) Evaluation of sub objective factor set $A_2$:
   
   $P_2 = Q_2^T \cdot A_2 = (0.2815, 0.4845, 0.2340, 0)$

3) Evaluation of sub objective factor set $A_3$:
   
   $P_3 = Q_3^T \cdot A_3 = (0.2686, 0.3472, 0.3842, 0)$

5.2. **Evaluation target layer**

Synthesize $P_1$, $P_2$ and $P_3$ results and get matrix A to evaluate target layer.

\[
A = \begin{pmatrix}
P_1 \\
P_2 \\
P_3
\end{pmatrix} = \begin{pmatrix}
0.3712 & 0.4712 & 0.1568 & 0 \\
0.2815 & 0.4845 & 0.2340 & 0 \\
0.2686 & 0.3472 & 0.3842 & 0
\end{pmatrix}
\]

\[
P = Q \cdot A = (0.1850, 0.4473, 0.2649, 0)
\]
6. Conclusions

1) According to the evaluation results, the weight value of bearing load, geological and foundation conditions, tower shape and service time on the stability of transmission tower above the goaf is "0.1061, 0.6334, 0.2605" respectively. It can be concluded that the geological and foundation conditions have a more significant impact on the stability of the tower, so we must pay attention to the impact of geological and foundation conditions on the performance of the transmission tower, especially, pay attention to the deformation and collapse of the goaf to ensure the stability of the tower.

2) The stability evaluation results of high-rise tower are "0.1850, 0.4473, 0.2649, 0", using the fuzzy comprehensive evaluation method and analytic hierarchy process to evaluate the specific indicators of each level from low to high. According to the principle of maximum membership, the stability evaluation results are relatively stable, and no additional measures are needed to improve the safety of tower temporarily.

3) It is necessary to pay attention to the ground separation, foundation settlement, tower material corrosion and other conditions in the goaf, evaluate safety and stability of the tower regularly, strengthen the deformation monitoring of the foundation of the high-voltage transmission line tower, establish good reinforcement and maintenance technical scheme to ensure the safe operation of the high-voltage tower and transmission line.

References

[1] Qian Minggao, Miao Xiexing and Xu Jialing 2007 Coordinated exploitation of resources and environment[J]. Journal of Coal 32 1
[2] Liu Wensheng 2001 Experimental study on the protection of ground high-voltage line by grouting in separated overburden[J]. Journal of Coal 26 236
[3] Guo Wenbing 2008 Prediction of surface movement in deep mining with wide strip[J]. Journal of Coal 33 369
[4] Xia Junwu, Yuan Yingshu and Dong Zhengzhu 2007 Study on the interaction mechanism of foundation, strip foundation and frame structure in mining area[J]. Journal of Geo-technical Engineering 29 537
[5] Wu Chaofeng and Cha Jianfeng 2017 Stability evaluation method for tower foundation of UHV transmission line over old goaf[J]. Journal of Wuhan University 50 402
[6] Guo Wenbing and Yong Qiang 2011 Study on the model of interaction between high-voltage line tower and foundation under the influence of mining[J]. Journal of Coal 7 1075
[7] Guo Wenbing and Deng Kazhong 2011 Current situation and Prospect of mining damage and protection technology of high-voltage transmission tower[J]. Coal Science and Technology 39 97
[8] Song Xuanmin, Wang Xiaoyi and Ji Xianyu 2017 Research Progress on the influence of mining subsidence on the safe operation of UHV power supply lines[J]. Journal of Taiyuan University of Technology 48 400
[9] Qiu Li and Zhang Jiayong 2007 Stability evaluation of coal mine roadway[J]. Journal of Hebei University of Science and Technology 29 6
[10] Zhang Jiayong, Guo Lishan and Qiu Li 2007 The application of fuzzy mathematics theory in the stability evaluation of coal mine roadway[J]. Mining Safety and Environmental Protection 34 23
[11] Li Hao, Xiao Junxian and Tian Tao 2012 Grey comprehensive evaluation of mine ventilation system based on AHP[J]. Coal Mine Safety 43 166
[12] Xu Jiaxin, You Bo and Shi Shiliang 2018 Risk assessment and prevention of deep well heat damage based on fuzzy analytic hierarchy process[J]. Mining Technology 18 68