Research Article

Analysis of the Influence of the Distribution and Development of Soil Caves on the Stability of High-Voltage Transmission Tower Foundations

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Abstract

As a kind of concealed flawed geology, karst geology easily forms soil caves, which may have a negative effect on adjacent transmission tower foundations. Since soil caves are continuously developed when surface water flows through soil, or groundwater levels fluctuate, the effect of soil caves on transmission lines in power transmission engineering needs to be investigated. In this paper, combined with an engineering case in western Hubei, first, FLAC3D finite element software is used to analyze the influence of a single underground soil cave during continuous development and expansion on 500 kV transmission towers. Considering the maximum allowable tilt value of the tower foundation, the stress state and deformation of the soil around the foundation are monitored during the calculation and analysis, and the maximum allowable radius of the soil cave in different positions is obtained. For example, the development radii of soil holes are 1.5 m, 2 m, and 2.5 m for burial depths of 7 m and 8 m, 9 m, and 10 m and 11 m, respectively, and the development radius of soil holes with a burial depth of 12 m and below can reach the maximum value of 3 m under actual working conditions. Then, the results of two simplified models of columnar and spherical development of the soil cave are compared, and it is found that columnar development is more in line with the actual situation. Finally, under the condition of a close-range double soil cave distribution, the influence of the size, depth, and gap between the two caves on the tower foundation is simulated. This study can provide references for the safe operation of transmission towers and the assessment of possible disasters in karst areas.

1. Introduction

Hubei Province is located in the central intersection area of the national power grid. The Hubei Power Grid not only undertakes the power supply guarantee of the province, but also carries the important task of the "West-East electricity transmission project" and hydropower and coal power transmission, playing an important role in the development of the national power grid. As a widely used power transmission medium, a high-voltage transmission tower is an important part of power construction. With the rapid development of power construction and the gradual implementation of national network construction, high-voltage transmission towers will be built in large numbers in Hubei. To reduce the impact of towers on the human living environment, a large number of towers will be built in mountainous areas and other sparsely populated areas. However, there are a large number of carbonate rock interlayer geological areas in Hubei Province, and soil caves are widely distributed and continuously developed. Therefore, it is very important to consider the influence of soil cave development on the stability of transmission tower foundations for their normal service.

As the bearing foundation of various buildings and structures, the soil medium has a vital impact on its stability. The influence of foundation soil on superstructure is an important topic worthy of continuous research and exploration. For example, Tavakoli et al. [1] carried out nonlinear dynamic analysis of high-rise buildings on the basis of three different types of soil media. Masahiro Iida [2] proposed a
three-dimensional simplified nonlinear method based on input seismic wave field to check the nonlinear behavior of soil-building interaction and compared and analyzed the buildings based on linear, nonlinear, and liquefied soil. It was found that the response of buildings in liquefied soil was too large. Dimitrios Sotiriadis and others [3] analyzed the damage effect of buildings subjected to earthquake under the conditions of nonlinear soil-foundation-structure interaction. Y. Tang et al. [4] studied the soil-structure interaction mechanism of buildings near deep foundation pit and analyzed that this mechanism may cause damage to masonry houses. Heidarzadeh et al. [5] used FLAC numerical software to excavate the soil medium around a tunnel to ensure that the stress released by the soil around the tunnel is gradually eliminated. In addition to the above studies, some researchers have improved the characteristics of soil. For example, Kangar R and others [6] improved the shear strength and its parameters by adding nanoclay to the soil; however, these researchers determined that the substantial addition of nanoclay will have a negative impact on the soil strength parameters. In addition, more attention has been paid to the research of geoenvironmental engineering and stability analysis in soil foundation. Zhao W and others [7] revealed the mechanical behavior caused by different types of anchorage failure based on PLAXIS finite element method and determined that the failure location occurred at the top of pile wall or near the bottom of foundation pit. Dong MM and others [8] used the displacement least square method to evaluate the excavation stability of the deep foundation pit and optimized the key parameters of the supporting pile. Huang et al. [9] analyzed the influence of landslide surface deformation on the deformation of the tower foundation on the slope under the conditions of extreme rainfall and local road excavation and proposed a quantitative calculation method for the inclination of towers under landslide disasters by using Geo-Studio finite element software. There are many carbonate intercalation lithologies in Hubei, China. As special soil media, they have great influence on the safety of geotechnical engineering. In particular, soil holes in carbonate interlayer lithology and their development have an important impact on the construction and operation of the upper transmission tower.

In recent years, research on the stability of soil caves has been carried out. In most studies, soil caves are usually regarded as circular or elliptical cavities, so that mechanical methods can be used. For example, Edwards [10] calculated a four-part stress solution when five stress states acted on an ellipsoidal cavity. Liao et al. [11] calculated the limit stress values of key points on an ellipsoidal cavity wall under the action of triaxial stress by using the superposition principle and evaluated the stability of the cavity on this basis. Based on complex function theory, Zhao et al. [12] calculated the stratum stress and the maximum and minimum principal stress of any section under the coupling action of multiple loads and introduced the Griffith strength criterion to evaluate the stability of karst caverns. Wang and He [13] established a formula for the limit equilibrium height of a critical soil cavern according to the theory of the Pretzler equilibrium arch of an underground cavern. Chen et al. [14] proposed an expression for the stability coefficient of a soil cave according to the Boyle-Mariotte law and established a mechanical model of karst collapse caused by falling groundwater.

Regarding the stability of structures in karst geology, such as foundations and tunnels, there have been many research results. For example, Liu et al. [15] qualitatively evaluated the influence of geological structure, structural plane, rock layer property, karst cave body shape, and groundwater on the foundation stability of karst caves on the basis of the theoretical research results of foundation stability in karst areas. Based on the upper bound theorem, Huang et al. [16] derived an analytic expression for the collapse surface through the variation calculation and deduced the minimum distance between a cave and a tunnel. Huang et al. [17] established an attribute recognition model for evaluating the safety thickness of concealed karst caves and tunnels based on attribute mathematics theory. Liu et al. [18] derived the analytical solution of the critical safe distance between a regular karst cavern and tunnel by using the upper bound theorem of limit analysis. Xue et al. [19] studied the influence of karst caves of different sizes and locations on the displacement and stability of tunnel surrounding rock, established the evaluation index of disturbance degree, and quantitatively evaluated the risk level of karst caves. Zhang et al. [20] studied the influence of cave shape on the stability and minimum safe thickness of a tunnel surrounding rock by establishing a 3D water-filled cave and tunnel model. However, there have been few studies on the stability of transmission towers in karst areas, and there is no research on the stability of transmission tower foundations under the conditions of the development of underground soil caves.

In addition to the distribution of a single soil cave, in reality, there are distributions of multiple short-distance soil caves. At present, researchers have studied the stability of soil cavities and its influencing factors under the condition of multicavity distribution. For example, Zhao et al. [21] calculated the maximum and minimum stress values at any point in the soil layer with double holes through a second iteration based on the Schwarz alternate method. Similarly, the Mohr–Coulomb strength criterion was also used to evaluate the stability of the soil holes. There is still no research on the influence of the distribution of close double holes or multiple holes on adjacent structures. However, for the study of the interaction between two or more soil caves (independent development) and their influence on the superstructure, the related research results for the short-distance tunnel can be referenced. For example, Li et al. [22] analyzed the stress characteristics and stability of the middle partition wall of double tunnel excavation through theoretical and numerical methods combined with field measurements. Li [23] used FLAC3D to simulate the stability of the surrounding soil in the process of double tunnel excavation and evaluated the influence of double tunnel excavation by monitoring the settlement and the stress change in the soil. These research results also indirectly reflect the feasibility of FLAC3D and other geotechnical numerical
Software for the simulation of geotechnical engineering problems related to the distribution of double soil caves.

Therefore, in this paper, based on the actual case of soil cave development under a tower foundation, research on the influence of an underground karst cave on the stability of a transmission tower foundation is conducted by using FLAC3D finite element software, and the limit conditions of the soil cave under different burial depths are obtained. For the influence of the interaction of close double caves on the stability of the transmission tower foundation, the influence of soil cave depth, distance, and size on the stability of the transmission tower foundation is also obtained. The advantage of this research is that it can be used to quickly determine whether soil caves under a transmission tower need safety measures to ensure the normal operation of the towers. Using this approach, the squandering of resources caused by the treatment of all adjacent soil holes can be avoided. The research results can provide references for similar projects and provide a certain analysis method for transmission line selection and transmission tower foundation design in karst areas. The disadvantage of this research is that, to facilitate the analysis of the impact of soil holes on the stability of transmission towers, through the selection of soil holes with specific locations and shapes, there is a certain regularity, which is different from the soil holes under actual working conditions. Subsequent researchers can further analyze and study this issue by changing the distribution and shape of soil holes.

At present, researchers mainly study and analyze the stability of the soil cave itself, the impact of the soil cave on the foundation and tunnel, and the stability under the distribution of multiple soil caves. However, there have been few studies on the foundation of transmission towers for the distribution and development of soil caves. Transmission towers are the main transmission carriers of transmission circuits in the world, and the stability of their foundation is very important to the operation period of transmission lines. Therefore, in this regard, this study explores the stability of tower foundations with single-hole development and double-hole development, which has great reference value for the construction and operation of transmission tower foundations and reduces unnecessary economic losses.

This research considers that, under the premise of not affecting normal operation of the transmission tower, the soil holes at different depths under the tower foundation have a certain limit development radius, and the radius increases with decreasing burial depth. When a soil hole is buried to a certain depth, the influence of the radius on the foundation is ignored. Under the distribution of double holes, this research considers that the buried depth, spacing, and radius of double holes jointly affect the stability of the upper foundation.

2. Engineering Background

The Enshi to Shuibuya II circuit 500 kV transmission line project was invested and built by the State Grid Hubei Electric Power Company in China. The landform types of this project area are mainly mountainous, which belongs to the humid climate of the middle subtropical monsoonal mountain area. The major soil type of the project area in the Ensch-Shuibuya II circuit is calcareous soil. According to the survey data, there are soil caves in the strata of this area. The caves discovered by investigation are all hollow holes with heights of 1 to 6 m, and the soil caves are mostly distributed in the clay layer above the bedrock.

The types of transmission tower foundations in this project area include rock-embedded foundations, excavation foundations, and cast-in-place slab foundations. In this paper, the excavation foundation, which is widely distributed in the soil cave area, is taken as the research object. According to the data of the as-built drawings, foundation leg C of this tower is configured as T2B, with a designed outcrop of 0.8 m, a designed buried depth of 4.3 m, and an actual outcrop of 0.1 m. The other three legs are configured with rock-embedded foundations. The practical height of this type is ZB 33–36 m, and the forces on the foundation are $N = 1000 \text{kN}$, $X_N = 150 \text{kN}$, $T = 900 \text{kN}$, and $X_T = 900 \text{kN}$.

On April 3, 2017, during the inspection of tower No. 260 of the 500 kV transmission line, a suspected soil cave was found by the inspectors at the base of tower leg C, as shown in Figure 1. Due to the timely investigation of the site by inspectors, the exposed soil cave was discovered and dealt with in time, and after examination and calculation, the soil cave had little effect on the foundation of the transmission tower. If there is an undiscovered small soil cave under the tower foundation, then the soil cave will develop gradually with time during the future operation of the transmission line. Hence, the development of soil caves can necessarily affect the foundation of the tower and may cause the tower to tilt or even be damaged. Therefore, it is necessary to analyze how the development of soil caves can affect the stability of transmission tower foundations. Based on this project, the stability of tower foundations above soil caves under different development modes and development degrees of caves is analyzed in this present research paper.

3. Numerical Model

3.1. Hypothetical Conditions and Limitations

3.1.1. Hypothetical Conditions. Due to the complex geological environment in actual engineering, the shape and other characteristics of the soil cave are affected by many factors, and the following assumptions are made to carry out numerical simulation calculations:

(i) It is assumed that the soil cave is at the most disadvantageous position, which means that the compression column, the tension column in the tower foundation, and the cross section of the soil cave are in the same plane, and the soil cave is directly below the compression column.

(ii) Assume that the hole is circular in shape and is completely within the overburden. The soil cave is simulated and analyzed in the form of cylindrical development.
As the formation process of the soil cave is relatively slow, the soil stresses near the soil cave are in a stable equilibrium state. Thus, the time effect of gravity and the effect of the tectonic stress field are not considered in the calculation. As an external load, the transmission tower load is assumed to be applied one time, regardless of the construction process.

In practice, there are fillings in soil caves, but the fillings are distributed loosely, and their strength is very low. Therefore, the caves can be set as empty in the simulation calculation.

In the case of a double soil cave distribution, it is assumed that the two caves are completely located in the upper carbonate clay layer and lie on the same horizontal line.

3.1.2. Limitations. Based on the above assumptions, it becomes convenient to analyze the influence of the underlying soil cave on the stability of the transmission tower foundation. Although the assumptions simplify the simulation process, there are still some limitations as follows:

(i) Under actual working conditions, the location relationship between the soil holes and tower foundation is complicated. Only the distribution of soil holes directly under the tower foundation is analyzed in this paper. In addition, the actual shape of the hole is not strictly circular. Of course, the shape of the soil cave will have a great influence on its stability. Therefore, in a follow-up study, the influence of soil cave development on tower foundations can be further analyzed by changing the shape and location of the soil cave.

(ii) In the analysis for the double soil holes case, the two soil holes are assumed to be in the same horizontal position, which is just a special case of actual engineering. The research results in this paper are only for this special case. However, the research method mentioned in this paper can also be extended to different soil cave distributions.

(iii) Because the expansion of soil holes is relatively slow, the time effect of soil hole development is ignored in this study, and the different states of soil holes after expansion are used as the simulation of calculation cases.

(iv) In this paper, the allowable value of the settlement difference between the compression column and tension column is used to determine the instability of the transmission tower foundation. Therefore, the study only focuses on the foundation form with relatively independent tower legs and is not suitable for the overall joint foundation.

3.2. Numerical Model and Parameter Setting. Figures 2(a) and 2(b) are schematic diagrams of the numerical models in the case of a single soil hole distribution and a double soil holes distribution, respectively. As the figures show, the diameter of the cave is R, the radius is r, and the depth of the cave is H. In the models, the stratum is divided into two layers, namely, the clay layer and limestone layer, and the soil cave is located in the upper clay layer. Without considering the influence of reinforcement, the transmission tower foundation is set as C30 concrete. The physical and mechanical parameters of each soil layer and the C30 concrete parameters are set as shown in Table 1. In FLAC3D software, the Mohr–Coulomb model is adopted for both soil layers. The load parameters are set as described in Section 1.

Figure 3 shows the numerical calculation models built in FLAC 3D software. First, a 3D model with a size of 40 m x 18 m x 40 m is established by using Rhino, and the grid of the geometry is divided. The grid of the models should not be too dense or too sparse because the computational efficiency will be greatly reduced in a dense mesh condition. However, it is difficult to guarantee the computational accuracy in a thick mesh condition. Therefore, the grid settings near the soil caves are dense, while those far away from the soil caves are sparse. Then, the grid data are imported into FLAC3D software by a conversion program. In FLAC 3D, the boundaries of the x direction and y direction on both sides are all horizontal constraints, the bottom z direction is all constraints, and the top is set as a free boundary.
3.3. Verification. To verify the accuracy of the numerical method, the theoretical solution of the stresses on the side of the circular soil cave in the plane under a uniform load of the foundation [24] was compared with the numerical results in the present study. As shown in Figure 4, the dimension of the $y$ direction is set longer in numerical modelling, so it can be simplified as a plane strain problem. The grid division and boundary setting of the model in this section are the same as those in Section 3.2. Since only the stress values in the $x$, $y$ and $z$ directions of the monitoring points can be obtained during numerical calculation, the major and minor principal stresses can be calculated according to the following formula:

$$\sigma_1, \sigma_2, \sigma_3 = \sigma_{xx}, \sigma_{yy}, \sigma_{zz}$$

Table 1: Physical and mechanical parameters of the model.

| Parameters | Weight $\gamma$ (kN/m$^3$) | Cohesive force $c$ (kPa) | Shear strength $\phi$ (°) | Elasticity modulus (MPa) | Poisson’s ratio |
|------------|-----------------------------|--------------------------|--------------------------|--------------------------|----------------|
| Clay       | 18.5                        | 39.5                     | 14                       | 12                       | 0.30           |
| Limestone  | 26                          | $3 \times 10^6$          | 35                       | $1.4 \times 10^4$        | 0.25           |
| Concrete   | 25                          | —                        | —                        | $3 \times 10^4$          | 0.2            |

Figure 2: Schematic diagram of the computational model. (a) Single cave. (b) Double caves.

Figure 3: Numerical simulation models of soil cave development. (a) Single cave. (b) Double caves.
The results of the comparison calculation are shown in Table 2. Clearly, under the same calculation example, the results of stress components at different positions of the soil cave calculated by theory and numerical simulation are very close, and the variation trend of principal stresses obtained by numerical calculation with different monitoring positions is basically consistent with the theoretical results. Thus, the accuracy of the numerical method in this paper is verified. In addition, from the calculation results, the numerical results of the major principal stress are generally smaller than the theoretical results, while the numerical results of the minor principal stress are generally larger than the theoretical results. The main reason for the difference in the results is that the plane problem is completely used in the theoretical calculation, while the size of the model in the y direction is finite, which has some influence on the results in the numerical calculation. Moreover, the material parameter setting in numerical calculation is not ideal elasticity.

According to the limit equilibrium theory,

\[
\begin{cases}
\sigma_1 = \sigma_3 \tan^2 \left( \frac{\pi}{4} + \frac{\phi}{2} \right) + 2c \cdot \tan \left( \frac{\pi}{4} + \frac{\phi}{2} \right) \\
\sigma_3 = \frac{\sigma_1 \pm \sqrt{\left( \frac{\sigma_1 - \sigma_3}{2} \right)^2 + 4c^2 \tan^2 \left( \frac{\pi}{4} + \frac{\phi}{2} \right)}}{2} \end{cases}
\]  

(1)

If \( \sigma_1 < 0 < \sigma_3 \) and \( \phi < \pi/4 \), then it can be judged that the soil cave has good stability, but the soil cave is in an unstable state. According to the results in Table 2, it can be concluded that the soil cave in this example is in a stable state.

4. Analysis of Simulation Results for a Single Soil Cave

According to experience, it can be predicted that the uneven settlement of the tower foundation will be more obvious when the soil cave in the same position develops continuously. The closer the soil cave is to the tower foundation, the more sensitive the tower foundation will be to the development of the soil cave. Therefore, in this section, calculations are carried out for the conditions with the most unfavorable locations, and the influence of soil cave development on the stability of the tower foundation is analyzed.

Through simulation, the inclinations of the tower foundation under different buried depths (H) and different radii of the soil hole (r) are calculated. The stability of the transmission tower foundation is analyzed by taking the settlement difference between the compression and tension tower legs of the transmission tower and the plastic state of the soil near the transmission tower as the control indices. According to clause 5.2.2 of Technical Specification for Design of Overhead Transmission Line Tower Structure (DL/T5154-2012), the maximum slope of foundation is 5%.

During the calculation, the radius of the soil cavity grows from 0.5 m to 3 m and increases by 0.5 m each time, while the
foundation burial depth is calculated from 7 m to 18 m and increases by 1 m each time. The vertical displacement of the bottom midpoint of the two tower legs and the change in the stress state of the soil near the cave and the tower legs are monitored. When the foundation inclination exceeds 50 mm, or the soil near the tower foundation is completely destroyed, the failure of the tower foundation will be considered to be the instability. The results are shown in Table 3. The results in Table 3 reflect that the foundation inclination increases with increasing \( r \) under the premise that the depth \( H \) is the same. Conversely, on the premise that the development of the soil cave is the same, the foundation inclination decreases with increasing burial depth \( H \).

### 4.1. Instability Analysis of the Tower Foundation

As shown in Figure 5, when the buried depth of the soil cave is 7 m, the foundation inclination varies linearly during the development of the soil cave radius from 0.5 m to 1.5 m, and the inclination is less than 50 mm. In the subsequent development process of the soil cave, the curve shows a nonlinear change, and the inclination increases sharply, indicating instability failure of the foundation. Therefore, it is concluded that the maximum critical value for the development radius of a soil cave with a burial depth of 7 m is 1.5 m.

When the buried depth of the soil cave is 8 m, the tower foundation inclination curves change linearly in the early stage of soil cave development. After the radius of the soil cave increases to 1.5 m, as shown in Figure 6(a), the soil around the tower foundation begins to shear, but the overall stability of the tower foundation is good. When \( r = 2 \) m, the calculated foundation inclination is 64.26 mm, and shear failure occurs in the soil around the tower foundation completely, as shown in Figure 6(b). The value of foundation inclination increases nonlinearly, and the tower foundation has been completely unstable ever since. For safety reasons, the maximum critical value of the radius for the development of a soil cave with a buried depth of 8 m can also be determined to be 1.5 m.

Similarly, the maximum foundation inclination can be calculated, and the stress state diagram of soil near the soil cave can be obtained under the condition of different buried depths and radii. For example, Figure 7 shows the stress state diagram of soil around the soil cave at a depth of 9 m. According to the control standard mentioned above, the maximum radius of the soil cave can be obtained at each buried depth. For instance, the calculated maximum development radius at 9 m is 2 m, while that at 10 m and 11 m soil caves is 2.5 m.

### 4.2. The Stable State of the Tower Foundation

As shown in Figure 8, the settlement of the foundation caused by the development of soil caves with a buried depth of more than 12 m is within the safe range (50 mm), and the settlement curve changes approximately linearly with the radius of the soil caves.

The working condition \( H = 12 \) m is selected for analysis, as shown in Figure 9. The soil mass near the tower foundation is completely stable during the development of the soil cave from 0.5 m to 1.5 m. Then, some shear failure occurs in a small part of the soil near the tower foundation during the development from 1.5 m to 3 m, which has little influence on the whole stability of the tower foundation. During this development process, shear failure occurs in the soil near the soil cave, which takes the form of an X-type failure. As the radius increases, the shear zone also expands. Although the abovementioned effect on the tower foundation is small, to ensure the safe and efficient operation of the tower, it is suggested that some remedial measures should be taken when the radius of the soil cave develops to 3.0 m.

| Inclination/mm | \( H \)/m |
|---------------|----------|
| 7             | 8        | 9        | 10       | 11       | 12       | 13       | 14       | 15       | 16       | 17       | 18       |
| 0.5           | 1.40     | 1.35     | 1.29     | 1.24     | 1.11     | 1.06     | 1.00     | 0.88     | 0.82     | 0.81     | 0.80     | 0.76     |
| 1.0           | 9.95     | 9.70     | 9.32     | 8.75     | 8.15     | 7.94     | 7.36     | 6.88     | 6.57     | 6.50     | 6.35     | 6.32     |
| 1.5           | 38.76    | 17.38    | 15.93    | 15.25    | 15.13    | 15.00    | 15.08    | 14.60    | 14.09    | 13.94    | 13.35    | 13.06    |
| 2.0           | 225.22   | 64.26    | 28.38    | 24.71    | 24.26    | 23.07    | 18.92    | 18.80    | 18.77    | 18.74    | 18.18    | 18.15    |
| 2.5           | 605.81   | 276.67   | 167.65   | 36.58    | 31.65    | 29.31    | 28.99    | 28.43    | 28.02    | 27.57    | 25.99    | 25.40    |
| 3.0           | 1275.76  | 689.71   | 420.67   | 99.36    | 56.23    | 40.00    | 38.67    | 37.51    | 36.61    | 35.72    | 32.72    | 32.40    |

**Table 3: Calculated inclination values of the tower foundation.**
5. Influence of the Soil Cave Development Pattern

5.1. Two Modes of Soil Cave Development. It is known from experience that a soil cave will continue to develop and expand under the condition of surface water erosion or ground water level fluctuations, and the cave will form an irregular-shaped empty cavity with relatively loose fillings. Typically, caves can be simplified as a circle or a semicircle when analyzing the stability of a soil cavity and its influence on the stability of a building foundation. When considering the spatial distribution of soil caves, it is usually assumed that caves develop and enlarge in the shape of cylinders or spheres, as shown in Figure 10(a) and Figure 10(b). For example, Jia et al. [25] regarded a soil cave as a hemisphere to simulate the collapse evolution law of soil caves. However, He et al. [26] regarded a soil cave as a cylinder to analyze the collapse evolution.

In this paper, the development of a soil cave is analyzed and calculated according to the simplified cylindrical shape shown in Figure 10(a). To ensure the validity of the calculation in this paper, two simplified models of soil cave development are compared and analyzed in this section. For the same depth \(H\) and the same radius \(r\) of the soil caves, two 3D calculation models are established, as shown in Figure 10. Other parameters are set in accordance with Section 2.

5.2. Results Comparison. Three working conditions of buried depth \(H = 11\) m, \(12\) m, and \(13\) m are selected for simulation and comparison, and the influence on the stability of tower foundation under these working conditions is analyzed in the case of spherical and cylindrical soil cavity development models. Table 4 shows the calculated results under the two development modes of the soil cave.

As shown in Figure 11, the trends of the calculated foundation settlements under these two modes are similar, and the value difference is small, which reflects the feasibility...
of the simplified model. In addition, the calculation results in cylindrical mode are larger than those in spherical mode overall. Combined with engineering practice, the simplified calculation results based on cylinder development can be used to more safely judge the stability of the foundation and carry out the necessary safety protection in time, so it meets the actual requirements.

6. Analysis of Simulation Results for Double Soil Caves

In this section, the radius, buried depth, and distance between the two soil caves are taken as the major parameters to analyze the influence of a soil cave on the stability of a transmission tower foundation.

6.1. Influence of the Distance between the Two Caves L

To study the influence of the distance between two soil caves $L$ on the stability of the transmission tower foundation, the special case $H = 9$ m is selected to analyze the foundation inclination value under different working conditions. Figure 12 shows the curves of the foundation inclination value with $L$ under four cases with different soil cave radii. From Figure 12, under the condition of the same radius of the soil
the inclination of the tower foundation decreases with increasing distance $L$, and the slope of the curves decreases with increasing $L$. The curves become increasingly flatter, indicating that the soil cavity spacing has less influence on the foundation with increasing $L$. The intersection points of each curve and the dotted line in the figure are the minimum horizontal spacing of the safety and stability of the foundation corresponding to the different radii of the soil cave under the condition that the buried depths are consistent.

6.2. Influence of the Buried Depth $H$. In this section, the radius of the soil cavities is set as a constant value, $r = 3$ m. For the soil cavity spacings $L = 1$ m, 3 m, 5 m, 7 m, and 9 m, the corresponding foundation inclination values to each working condition are calculated, as shown in Figure 13. As seen from Figure 13, under the condition of the same distance between the soil caves, the stability of the tower foundation keeps rising with the increasing buried depth of the soil caves. However, due to the large radius of the soil hole, under the conditions of $L = 1$ m, 2 m, and 3 m, the settlement of the tower foundation is eventually higher than the limit value, so it needs to be filled in advance. When the buried depth is large, the slope of the curves begins to decrease slowly; that is, the influence of the buried depth on the stability of the tower foundation decreases.

For the case $L = 1$ m, the calculated stress state diagrams and the deformation path diagrams of the soil mass corresponding to $H = 10$ m, 12 m and 14 m are shown in Figure 14. From the figures, with increasing depth of the soil cave, both the stresses and the deformation of the soil near the foundation gradually decrease. However, the inclinations of the tower foundation under the three working conditions are 136.95 mm, 113.09 mm, and 101.04 mm, respectively, all above the limit value. Hence, the tower foundation corresponding to $r = 3$ m and $L = 1$ m has poor stability.

6.3. Influence of the Radius of the Soil Cave $r$. Figure 15 shows the calculated foundation inclination values with increasing $r$ at buried depths of 10 m and $L = 1$ m, 3 m, and 5 m. As shown in Figure 15, the variation laws of the three curves are similar. On the premise that the distance between the soil caves is constant, the foundation inclination of the tower increases with increasing $r$. The curve of the soil cave with a radius less than 2 m increases linearly, while the curve of the soil cave with a radius more than 2 m increases nonlinearly.

As shown in Figure 15, the larger the distance between the two soil caves, and the smaller the radius of the soil cave,
Figure 14: Stress state and deformation path diagram \( (r = 3 \text{ m}) \) \( (L = 1 \text{ m}) \).

Figure 15: Curve of the foundation inclination varying with the radius of the soil cave \( ((H) = 10 \text{ m}) \).
the more stable the foundation of the tower. In contrast, the smaller the distance between the two soil caves, and the larger the radius of the soil cave, the more unstable the foundation of the tower.

7. Conclusions

Based on the actual project, FLAC3D is used to simulate the development of soil caves, and the effect of soil cave development on tower foundations is obtained in this paper. The main conclusions are as follows:

(1) On the premise of the same buried depth $H$ of the soil cave, the inclination of the tower foundation increases with increasing development radius $r$. On the premise of the same development radius of the soil cavity, the inclination of the tower foundation decreases with increasing depth $H$.

(2) In the case of a single soil tunnel, the maximum radius of soil tunnel development with burial depths of 7 m and 8 m is 1.5 m, the maximum radius of soil tunnel development with a burial depth of 9 m is 2.0 m, and the maximum radius of soil tunnel development with burial depths of 10 m and 11 m is 2.5 m. When the radius of the soil tunnel under different burial depths exceeds the maximum allowable radius, it is considered that the pole tower foundation is unstable and damaged. The development radius of the soil tunnel with burial depths of 12 m and below can reach the maximum value of 3 m under actual working conditions; that is, it is considered that the development of the soil tunnel with burial depths of 12 m and below has a negligible impact on the stability of the tower foundation. The above data show that the deeper the buried depth of the soil tunnel, the larger the development radius of the soil tunnel, and with a continuous increase in the buried depth, the impact of the soil tunnel on the upper foundation is ignored.

(3) The results of the cylindrical and spherical development models of the soil cave are similar. The simplified calculation according to the cylindrical development model of the soil cave is more in line with the actual demand.

(4) In the case of double soil caves, the stability of the tower is affected by the radius, spacing, and burial depth of the underlying soil holes. The larger the horizontal distance between two caves, the deeper the depth, and the smaller the radius, the better the stability of the tower foundation. In contrast, the smaller the distance between two caves, the shallower the depth, and the larger the radius, the worse the stability of the tower foundation.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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