Research on the Cave Exploration Technology of Overhead Transmission Line Tower Foundation

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Abstract. Overhead transmission lines are the main form of high-voltage and UHV long-distance transmission. When the line path passes through limestone areas, mining areas and others, the possible existence of karst caves and mined-out areas under the tower base will have a greater impact on the stability of the foundation. According to previous detection experience, different underground cave forms and detection requirements need to choose suitable detection technology to obtain better detection results. This paper will explain the different detection technologies, combine multiple overhead line engineering practices, study the detection technology of underground caves, and guide the subsequent exploration of the tower foundation underground caves. Finally, carry out three-dimensional geological modeling of the exploration data, and study the application of three-dimensional data processing and display technology in the exploration of the line tower base cave. Through the above summary, analysis and experimental research, a complete set of technical solutions for the exploration of tower foundation caves on overhead transmission lines has been completed, laying the foundation for the further development of subsequent detection technologies.

Keywords. Transmission Line tower foundation; Cave detection; Geophysical technology; 3D geological modelling

1. Introduction
To meet the power demand in economic construction and social development, as an important part of the power system, a large number of high-voltage transmission line projects are surveyed, designed, constructed and put into production every year. Due to channel occupation by the existing high-voltage transmission line projects, coupled with urban expansion, land acquisition and other factors, there are currently fewer and fewer selectable paths for new overhead transmission line projects. New line engineering path must pass through limestone karst development areas, mined-out areas where there are underground caves. The presence of these underground caves has brought great safety hazards to the tower foundation.

Geophysical exploration technology (abbreviated as geophysical technology) uses special equipment to observe the electrical and wave impedance differences between geological bodies and caves, and restores the relative positions and cave sizes of geological bodies and caves via inversion of observation data, which is a non-destructive detection method with high work efficiency and low cost. Geophysical technology has many applications in the detection of underground caves, which is widely used in large-scale projects such as highways, railways, electric power, and water conservancy, demonstrating a great role. However, geophysical technology has multiple interpretations for its own results. Different underground cave forms and detection requirements require one or more suitable detection technologies to achieve better detection results. Therefore, this paper selects several typical cave detection cases in transmission line tower foundation projects, studies the applicability and detection effect of geophysical technology, and also discusses three-dimensional display of some detection results.

2. Tower foundation cave detection features
2.1 Tower foundation types
The transmission line tower foundation bears not only the pressure of the tower body, but also the pull-out force brought by wind load. The geotechnical engineering conditions and design use of the foundation determine the tower foundation types, which include general foundation, cast-in-place pile foundation, prefabricated foundation and rock foundation, etc. [1]. If the caves (earth caves, karst caves, mined-out areas, etc.) under the tower foundation are not treated, once the cave collapses, it will directly cause the foundation to tilt or collapse, causing huge losses to the entire transmission line.

2.2 Detection characteristics
The target of tower foundation cave detection is the possible tower foundation along the line project. The detection purpose determines its detection characteristics different from other projects, mainly in the following aspects:

(1) Scattered detection points: Different from general site karst detection, the line tower foundation is distributed along the line engineering path, and the distance between adjacent tower foundations is generally several hundred meters, so the detection points are relatively scattered.

(2) Small detection range: Although the tower foundation has many design types, each foundation occupies a small area, generally within the range of 30m×30m. The survey line layout is shown in Figure 1 below. 4 survey lines are generally arranged along the tower legs in a "groined" layout.

(3) High precision requirements: The detection results are used as the basis for basic positioning and foundation treatment. In particular, larger-scale caves have higher requirements for accuracy in detection results, thus providing greater guiding significance for subsequent foundation treatment.

3. Technical methods

3.1 Ground penetrating radar
Ground Penetrating Radar, also known as GPR, is an electromagnetic detection method that locates and detects buried bodies or interfaces in underground space [2]. This method features high resolution and high efficiency, which has been recently widely used in the detection of underground caves (mined-out area, karst), bedrock surface, overburden thickness, crushed zone and underground buried objects (pipes, cables, etc.).

Since various media in underground space (such as different rock and soil layers) have different electrical properties and different dielectric constants, ground penetrating radar uses high-frequency electromagnetic waves (with dominant frequency of tens to hundreds of MHz) to detect the target body via its reflection on interface of different media. The transmitting antenna and the receiving antenna are used to transmit high-frequency electromagnetic waves and receive reflected waves, respectively. According to the two-way travel time of the received reflected signal, by analysis and processing of the received reflected waves, it is possible to determine the location of anomalous bodies, thus achieving the purpose of detecting underground anomalous bodies (caves, bedrock surfaces, etc.). See Figure 2 below for the schematic diagram of ground penetrating radar.
3.2 Transient electromagnetic method

Transient electromagnetic method (TEM), also called time-domain electromagnetic method, unearthed return circuit to emit a pulsed primary electromagnetic field (also called primary field) into the ground. Under the excitation of this primary field, induced eddy currents will be induced in the geological body of the underground space, and then induced electromagnetic field (secondary field) that changes with time will be generated [3,4]. By using the receiving coil to observe the secondary field, the response information can be processed and analyzed, thereby extracting the abundant geoelectric information of the underground geological body to achieve the purpose of detection and positioning. Its working principle is shown in Figure 3 uses

![Figure 3. Working principle of transient electromagnetic method](image)

Ground transient electromagnetic method has the advantages of easy penetration of high-resistance layers, sensitive response to low-resistance water-rich mined-out areas, underground caves, etc., simple and convenient construction, and high work efficiency.

3.3 High density electrical method

High-density resistivity method is an improvement of the conventional DC resistivity method. With the same basic principle as the traditional resistivity method, it is based on the electrostatic field theory and electrical difference of the medium [5,6].

The method is to arrange multiple electrodes on the survey line at the same time, combine them into a designated electrode device through the electrode conversion device, and then achieve observation of the apparent resistivity of multiple electrode distances on the multiple measuring points of the observation profile, shown in Figure 4. It has dual effects of resistivity profile method and sounding method. The method has the characteristics of numerous electrodes and high data collection density. The inverted electrical profile can directly and vividly reflect spatial distribution information of underground electrical anomalies. Combining the results of geological surveys, the spatial location, scale, and burial depth of geological bodies can be accurately judged. The method is widely used in the exploration of metal and non-metal mineral resources, urban geophysical prospecting, railway and bridge exploration, etc., which is also used in engineering geological explorations to find groundwater and underground caves (karst caves, mined-out areas).
3.4 Seismic imaging method
Seismic imaging method is a common shallow seismic reflection wave exploration method developed based on the best offset technique of reflection wave method [7,8]. The detection mode of seismic imaging method is as follows: the seismic wave is artificially excited at the shot point, and then received by a single (or multiple) geophone at the receiving point. After the instrument recording, the shot point and the detection point move forward at the same time by a certain distance (point distance). Then, seismic imaging time profile on a profile can be obtained by repeating the above project, shown in Figure 5.

The main characteristics of seismic imaging method include: fast data acquisition, but weak anti-interference ability and limited exploration depth; simple data processing and high resolution of seismic records; multiple geophones can be used to get seismic records with different offsets, so data explanation is quick.

3.5 Elastic wave CT
Computerized Tomography based on ray theory is an effective method for underground cave detection [9]. CT technology can be divided into elastic wave CT, resistivity CT and electromagnetic wave CT according to the different transmitted signals. The imaging principles of each method are basically the same. Take elastic wave CT as an example. As shown in Figure 6, a large amount of first wave travel time data (t) is obtained through sector test, and then the velocity profile image between two holes is obtained by solving a large matrix equation, so that location and size of the cave can be determined based on low velocity zone in the velocity profile image. The method is one of the most effective and accurate test methods so far.
4. Application examples

4.1 ±800kV Baihetan-Zhejiang UHV DC Transmission Line Engineering Application

The ±800kV Baihetan-Zhejiang UHV DC transmission line project starts at Xianfeng Converter Station in Butuo County, Liangshan Prefecture, Sichuan Province, and the line length is about 2193km (including large spans). The starting point of the line responsible by the Guangdong Institute is in Xingshan County, Yichang City, Hubei Province, and the end point is in Dongbao District, Jingmen City, Hubei Province. The line passes through Xingshan County, Yiling District, Yuan'an County and Dongbao District of Jingmen City, with a package section length of 151.5km, a tortuosity coefficient of 1.16, and the whole line is erected as bipolar. Where, the line sections of Yiling District and Yuan'an County of Yichang City pass through large limestone areas and mining areas with karst caves and mined-out areas underground, which brings hidden dangers to stability of the tower foundation.

(1) High-density electrical method combined with transient electromagnetic method for cave detection

The surface covering layer is mainly soil-based tower foundation, which is more suitable for detection by high-density electrical method. A number of towers were selected for the detection test. Take the A193 tower as an example. High-density electrical method combined with transient electromagnetic method was used for detection. The profiles from leg A to leg B in high-density electrical method and transient electromagnetic method are interpreted as shown in Figure 7 and Figure 8.
The detection results show that the cave is shown as a low-resistance anomaly in the profile. The center of the low-resistance anomalous area of the two methods is basically the same in the plane position, though with a certain difference in depth. Transient electromagnetic method has greater interpretation depth than high-density electrical method, but the anomalous scale is obviously small.

(2) Transient electromagnetic method combined with ground penetrating radar for cave detection

Tower foundation exposed in the surface bedrock is more suitable for detection with ground penetrating radar. A number of towers were selected for the detection test. Take A194 tower as an example. Ground penetrating radar combined with transient electromagnetic method was used for detection. The profiles from leg A to leg B in ground penetrating radar and transient electromagnetic method are interpreted as shown in Figure 9 and Figure 10.
The detection results show that the cave appears as a low-resistance anomaly in the transient electromagnetic interpretation profile and as a diffraction arc in the ground penetrating radar profile. The midpoint of the anomalous area is basically the same in the plane position between the two methods, with a certain difference in depth, as transient electromagnetic method has greater interpretation depth than ground penetrating radar.

4.2 ±500kV Bohe power plant-wolong transmission line engineering application

The starting point of the ±500kV Bohe Power Plant-Wolong Transmission Line Project is at Bohe Power Plant in Maoming City, and the end point is at the 500kV Wolong Substation in Yunfu City. To ensure safety of the 702 and 703 foundation towers in Yunfu section, the rock surface undulation and karst development under the tower foundation were investigated in detail to guide the subsequent karst treatment construction. Cross-hole CT tests were carried out on the 702 and 703 foundation towers. Take the corner tower 703 as an example. The tower foundation has a spacing of about 17 meters. Using the work program shown in Figure 11 below, the borehole extends 2 meters along the line of the existing tower foundation, and the karst development profile of the tower legs is tested from two directions.
Two vertical closed profiles of each tower leg are obtained as shown in Figure 12 and Figure 13. The profile explains the karst development area and the cave size based on the inversion speed change. Subsequent drilling and grouting treatments show that the drilled caves have a size consistent with the profile display size. Since A-leg and B-leg karst caves are filled, the actual grouting amount is smaller than expected, and the grouting amount of leg D is
basically consistent with the estimate.

5. Conclusions and prospects

5.1 Conclusion

Through detection test and research of multiple projects and multiple methods, the following conclusions are drawn for cave detection of overhead transmission line tower foundation:

1. Suitable detection method should be chosen according to site conditions of the tower foundation and the detection purpose. When the tower foundation surface has earth covering or thick soil, high-density electrical method, seismic imaging method or transient electromagnetic method should be selected; when the tower foundation surface bedrock is exposed, ground penetrating radar and transient electromagnetic method can be selected.

2. As the current main detection method, ground penetrating radar detection is simple in field operation and high in detection efficiency, but its detection depth is limited. In particular, when the groundwater level is shallow and the covering layer is thick, it is difficult to achieve expected detection results.

3. High-density electrical detection can well detect plane position and depth of the cave, but the detection efficiency is slightly low. Moreover, due to the "volume effect" in electrical exploration interpretation, the range of anomalous bodies is often larger than the actual cave volume. Sometimes, even false anomalies will be generated, which need to be discerned by combining other information.

4. Seismic imaging method has high resolution, but is greatly affected by the terrain and difficult to operate when the bedrock is exposed. It is more suitable for the detection of large-scale underground caves such as mined-out areas.

5. Transient electromagnetic method has strong adaptability to site topography and landform, and has high horizontal resolution, but often has too big depth in anomaly interpretation.

6. Cross-hole CT technology has high detection accuracy and can accurately depict the scope and shape of the underground cave along the borehole profile, but it requires a lot of drilling and field testing. Therefore, cross-hole CT technology is only recommended for more important and critical tower foundations to guide the precise treatment construction of underground caves.

5.2 Prospect

With the development of geophysical technology and computer technology, underground cave detection technology for transmission line tower foundation will continuously upgrade and develop, so there are prospects in the following aspects:

1. Transient electromagnetic method has made great progress in recent years, which is no longer limited to detection of deep geological bodies. In particular, the advancement of high-frequency transient electromagnetic technology enables increase in detection resolution, so that detection of shallow objects is possible. High-frequency transient electromagnetic detection has simple and efficient field operation, which can well adapt to the changes in different topography and landforms, so that cave plane location can be accurately positioned. Thus, it can play a great role in cave detection of tower foundation in transmission line projects.

2. Three-dimensional geophysical technology is more and more used in shallow surface engineering detection. Representatives include three-dimensional high-density electrical method [10], shallow three-dimensional seismic exploration, etc. Three-dimensional detection can well overcome several shortcomings in two-dimensional profile detection, which represents the development direction of engineering geophysical methods.

3. With the development of computer technology and BIM technology, achievements in three-dimensional geological modeling technology have ushered in a big explosion in recent years, and engineering applications have also begun in some fields [11], shown in Figure 14. The tower foundation scope is small and the modeling is relatively simple. If the transmission line tower foundation is three-dimensionally geologically modeled, it is possible to better integrate the results of multiple exploration methods and provide more intuitive and accurate basic data for the subsequent tower foundation design and construction.

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