Influence of Goaf on Stability of Transmission Line Tower Foundation

Siyuan Zhang 1, Zhichao Fan 1, Liang Sun 1, Jiaohui Qiu 2

1 Ordos Power Supply Branch of Inner Mongolia Power (Group) Co., Ltd., Ordos 017010, China
2 Transportation Institute Inner Mongolia University, Hohhot 010070, China

Abstract: There are various rock mass structures in the overlying strata of the goaf, such as cavities, cracks and separation layers. The phenomenon of under compaction with these structures still exists. Under the action of various natural forces, loads and other external forces, the broken rock mass in the relatively balanced goaf will produce structural deformation and compaction, resulting in surface subsidence. This paper expounds the surface subsidence of goaf from the aspects of surface subsidence mechanism, evaluation of surface stability of goaf and influencing factors of tower foundation stability, which provides a theoretical basis for the treatment of goaf.

Keyword: Goaf; Surface subsidence; Stability; Deformation.

1. Introduction

In the past two decades, China's economic construction has made amazing achievements. The rapid development of national economy is inseparable from the development and utilization of coal resources in China. At the same time, it also brings energy problems and sustainable development problems. It is understood that in the old energy mining bases in the central and western regions of China, there are a large range of mined out collapse areas and a large area of land subsidence. All kinds of damages cause the foundation bearing capacity of buildings and other building facilities above the goaf to decline, and even the foundation sinks seriously. The collapse of the goaf occurs from time to time. For example, in the central and western regions of China, these regions have a large population and have a greater demand for land use. With a high density of population, it is necessary to put the development of land into the use of mined out areas. In addition, in response to China's energy policy of "power transmission from west to East", many transmission line tower foundations are built on goaf. When the load of buildings, such as the foundation load of power transmission tower, is added to the goaf, the original stable goaf may be "activated", and the rock and soil mass in the caving zone above the goaf may be compacted and lack of support, resulting in the collapse of the underground residual cavity, resulting in additional displacement and deformation of the surface, thus causing the overall settlement of the surface buildings, and the buildings may have local cracking or even collapse at the same time. Such accidents have become an important problem on the road of urbanization in China, which seriously restricts the construction of railways, highways and bridges.

2. Research background

To study the mechanism of surface subsidence, it is necessary to understand the law of surface subsidence. Wang et al. obtained rock mechanics parameters by studying the geological conditions of Xingtai, and then obtained three stages of vertical deformation distribution and surface subsidence by using finite element simulation analysis, and the subsidence laws of each stage are different[1]. Lu et al. analyzed the actual data of Taiping Coal Mine and showed that in the process of mining subsidence, the strata movement followed the law of "equilibrium non-equilibrium new equilibrium", that is, the original equilibrium state was broken into non-equilibrium state, and finally reached a new equilibrium state through various processes of movement and deformation[2]. Pan et al. found that with the continuous advancement of the working face, the relative positions of the working face and the surface points are different at different times, so the impact of mining activities on the surface is also different. The movement of the earth's surface experienced a process from the beginning of the movement, to the violent movement, and finally stopped[3]. Zhang et al. found that the form of surface deformation is not completely the same with the different mining depth, mining thickness, mining method, geological structure, seam occurrence and other factors. If the ratio of mining depth to mining thickness is large, the change of surface deformation with time and space is
continuous and regular. If the ratio of mining depth to mining thickness is small or there is a large geological structure, the result is just the opposite, and large cracks or collapse pits may appear on the surface[4]. Peng found that when the length of the working face is unchanged, the coal wall compression value increases with the increase of mining depth, while the deflection value and total settlement value gradually decrease, and the total settlement value decreases faster; When the mining depth is constant, the working face length increases, and the coal wall compression value, deflection value and total settlement value increase[5]. Li et al. found through the actual measurement of three coal mines in Huaihe mining area that the overall subsidence coefficient of the mining area is large, which belongs to coal mining under the thick loose layer. The existence of the loose layer will expand the range of surface movement and increase the amount of surface subsidence. Therefore, the subsidence coefficient is larger where the loose layer is thicker[6]. From the above research results, it can be seen that there are indeed laws to follow for surface subsidence. These laws show that subsidence is a complex process that develops continuously with time and space, and has a close relationship with geological conditions, rock stratum properties and mining conditions, which provides a research direction for the further study of the causes of surface subsidence.

3. Influencing factors of tower foundation stability

With the gradual advance of underground coal mining face, generally when the distance from the opening of the cutting hole to the advancing of the mining face is equivalent to 1/4-1/2 of the mining depth, the mining impact will spread to the surface, causing surface subsidence, and a subsidence area much larger than the goaf will gradually form above the goaf, which is called surface movement basin or subsidence basin. The five indicators that often describe the movement and deformation in the surface movement basin are: subsidence, tilt, curvature, horizontal movement and horizontal deformation. Among them, subsidence, tilt and curvature belong to the movement and deformation in the vertical direction, while horizontal deformation (including tensile deformation and compression deformation) and horizontal movement belong to the movement and deformation in the horizontal direction. These surface movements and deformations will directly cause the destruction of the original stress balance state inside the high-voltage line tower and the change of the operating conditions of the high-voltage transmission line. The parameters of the high-voltage line tower, such as the foundation spacing, the distance near the ground, the line span, the conductor sag, the deflection of the suspension insulator string, etc., may be affected and exceed the required operating parameters, thereby inducing potential safety hazards.

Different types of surface movement and deformation have different effects on the high-voltage line tower, and the high-voltage line tower structure itself has certain stiffness, which does not completely deform with the surface deformation, but also restricts the surface deformation. Therefore, the high-voltage line tower is not consistent with the surface deformation. Therefore, it is very important to study the influence and damage of various types of ground movement and deformation on the high-voltage line tower, the law of its influence and damage, and the extent and size of its influence and damage, for the study of the cooperative deformation law of the high-voltage line tower structure, foundation and foundation under the influence of mining. It is worth noting that the movement, deformation and even destruction of the high-voltage line tower due to the influence of surface movement and deformation is not a single process, but the result of the joint action and interaction of various surface movements and deformation. The movement and deformation of the surface are also affected by the high-voltage line tower, that is to say, they are synergetic deformation.

3.1 Impact of ground subsidence

The surface subsidence caused by underground mining is transmitted to the upper high-voltage line tower structure through the foundation, resulting in the subsidence of the high-voltage line tower. Subsidence includes uniform subsidence and uneven subsidence, which will be discussed separately below.

3.1.1 Influence of uniform settlement

The suspension point of the empty line of the high-voltage line tower dropped from E1 to E2 by W. after sinking, the tension of the suspension point, the sag and the distance to the ground of the conductor, the position of the maximum sag and the inclination angle changed. However, the specification clearly stipulates that the distance between the conductor and the ground shall not be less than the value L listed in table 2-1 under the maximum calculated sag. If the mining thickness is 2M and the subsidence coefficient is 0.8, assuming uniform subsidence, the ground surface will sink by 1.6m, which will have a direct impact on the ground distance of the high-voltage line tower conductor, and it is very likely to exceed the regulations, resulting in potential safety hazards for the high-voltage line tower.

Fig. 1 Influence of uniform settlement on HV Line Tower

In addition, the large, gentle and uniform subsidence of the ground surface has little impact on the high-voltage line tower, and there is almost no additional force in the high-voltage line tower structure, so it generally will not cause damage to the high-voltage line tower. However, when the subsidence value is very large, sometimes it will bring serious consequences, especially in the mining area with high diving level, when the surface subsidence causes the high-voltage line tower foundation to be close
to or below the groundwater level, the foundation soil will be softened by water immersion or frost heave will occur under low air temperature, which will cause serious corrosion of the high-voltage line tower foundation and foundation. The underground metal parts of the high-voltage line tower (metal foundation, stay wire device, grounding device) are also prone to corrosion, which greatly reduces its strength and seriously threatens the safety and stability of the high-voltage line tower.

Most of the high-voltage line towers are in lattice configuration and have a split structure with four legs. The common foundation is split type. The high-voltage line tower should bear the combined action of up pulling, down pressing and horizontal shear force. The consolidation, movement and settlement of the ground surface, as well as the inelastic characteristics between the earth and the foundation, make the ground surface sink to produce pressure. In addition, the tower and various loads cause uneven settlement between adjacent foundations, resulting in a variety of combined loads, resulting in greater stress in various components of the tower.

3.1.2 Influence of uneven subsidence

At present, most foundations of high-voltage line towers are independent foundations. Compared with the overall foundation, independent foundations are more vulnerable to uneven subsidence. It can even be said that as long as the surface deformation caused by underground mining affects the foundation of the high-voltage line tower, uneven settlement will certainly occur, because the independent foundation of the high-voltage line tower has a certain root distance. If the four independent foundations are simply divided into two sides, the settlement of the independent foundations on both sides at the same time cannot be completely consistent, so uneven settlement will certainly occur in the dynamic deformation, However, the "even sinking" usually means that the high-voltage line tower sinks evenly from the beginning to the end. Relevant research shows that the settlement of high-voltage line tower foundation is basically consistent with the corresponding surface settlement. However, due to the fact that the high-voltage line tower structure has a certain stiffness and does not completely sink with the foundation settlement, the settlement of high-voltage line tower foundation is slightly smaller than that of the corresponding foundation. According to the cooperative deformation theory, if the foundation area is large, there will be partial foundation unloading and partial loading on the foundation ground, which is also one of the reasons for the difference between the settlement of foundation and foundation. However, through consulting a large number of literatures, no specific quantitative relationship between the high-voltage line tower and the corresponding surface movement and deformation has been found. The uneven settlement of the foundation will also cause redistribution of the foundation reaction of the building, and generate additional stress in the high-voltage tower structure. If the additional stress is greater than the allowable stress of the material, the high-voltage tower structure is very likely to be damaged or even collapsed. If there is a subsidence difference between adjacent towers, it will affect the near ground distance of the conductor, which mainly depends on the topographic characteristics along the line and the subsidence difference between adjacent towers. The high-voltage line tower is located in the middle of the collapse area, which is easy to cause the foundation of the high-voltage line tower to sink, retract and deform; When the high-voltage line tower is located at the edge of the collapse area, it is easy to cause inconsistent foundation subsidence on both sides of the high-voltage line tower. One side of the tower has a large subsidence value and slides down the basin, resulting in tilt deformation of the tower body.

When the foundation has uneven settlement, the high-voltage line tower may have two reactions: the first is that the high-voltage line tower structure moves and rotates as a rigid body with the foundation under its own rigid body performance, and the high-voltage line tower structure is not damaged; The second is due to the elastic properties of the materials constituting the high-voltage line tower. When the additional stress exceeds the elastic limit of the tower material, the geometry of the high-voltage line tower will change to adapt to the uneven settlement of the foundation. At this time, the high-voltage line tower structure will be damaged, and the stress of each node will also change.

3.2 Impact of surface inclination

Uneven surface subsidence is the direct cause of surface inclination. For buildings (structures) with small bottom area and large height (such as water towers, chimneys, high-voltage line towers, etc.), even if there is a slight inclination, high-rise buildings (structures) will cause a large horizontal component and overturning force distance under their own huge gravity. The overturning force distance will increase the inclination of high-rise buildings (structures), resulting in a vicious cycle. Therefore, high-rise buildings (structures) are very sensitive to tilt deformation. The inclination of high-voltage line tower refers to the deviation of each part of the high-voltage line tower from its original position due to the inclination of the ground surface. The inclination degree of the high-voltage line tower is expressed by inclination. The inclination degree Q of the high-voltage line tower refers to the ratio of the horizontal distance (s) of the top center offset of the high-voltage line tower to the original height (H) of the high-voltage line tower.

The impact of ground tilt on high-voltage line tower is complex. The objects of impact include high-voltage line tower and its foundation, suspension string, line span, etc., which are mainly reflected in the following three aspects: 1) Impact on high voltage line tower and foundation. The ground surface inclination caused by mining will cause the corresponding inclination of the high-voltage line tower foundation. The tower inclination caused by the Tower Foundation Inclination increases the overturning moment of the foundation and the tower, thus affecting the overturning stability of the tower and the foundation.
For the stepped foundation, the inclination of the tower also increases the shear stress between the steps.

2) Influence on span, sag and suspension string. After the high-voltage line tower is tilted, the span is the distance between the projections of the ends of adjacent towers on the horizontal plane. Due to the inconsistency of the tilt value of the high-voltage line tower, the span will inevitably be expanded or reduced. The change of span will correspondingly cause the change of line sag and ground proximity. The inclination of the high-voltage line tower will also cause the stress redistribution in the conductor. In order to maintain the stress balance between the gears, the suspension string will shift to balance the unbalanced tension between the gears. The suspension string will deflect to the side with high tension, which may also cause the discharge accident of the conductor to the tower head.

3) Impact on ground proximity. The conductor relaxation caused by the inclination of the high-voltage line tower and the reduction of the actual height of the tower after the inclination may cause the insufficient distance between the conductor and the ground.

3.3 Influence of surface curvature
Uneven ground tilt causes curvature deformation of the ground surface. There are positive and negative curvature deformations, and the positive and negative deformation make the surface convex and concave respectively. In general, surface tension deformation and positive curvature deformation, compression deformation and negative curvature deformation occur at the same time. If the contact area is large enough, the ground surface will change from the original plane to a curved surface. The convex or concave surface will change the contact state between the foundation and the ground surface, break the original stress balance state of the upper building, change the foundation reaction, and generate additional stress in the building. When the curvature deformation increases to a certain extent, the building will be damaged.

Curvature deformation is one of the main factors of building damage. According to the analysis of domestic observation data of buildings in mining areas, the curvature of buildings is 21.3%–78.4% of the surface curvature. For buildings in positive curvature area, the curvature transferred to buildings (structures) is larger, while for buildings in negative curvature area, the curvature transferred to buildings is smaller. The greater the stiffness of the building, the smaller the curvature transferred from the ground surface to the building.

In particular, curvature deformation has little effect on buildings with small bottom area, and has a greater effect on buildings with large length. For the high-voltage line tower, the size of its independent foundation is generally small, so the contact area between the high-voltage line tower and the ground surface is small, and the range of redistribution by the foundation reaction is small. Therefore, the effect of surface curvature deformation is less. In addition, the high-voltage line tower structure itself has a certain stiffness and is not easy to bend with the curvature deformation of the ground surface, so the effect of curvature deformation on the high-voltage line tower can be ignored.

3.4 Impact of surface horizontal movement
The horizontal movement of the ground surface will cause the corresponding translation of the foundation of the high-voltage line tower. If the high-voltage line tower of the whole line moves horizontally at a uniform speed along the line, the operation of the line will not be affected. If the horizontal movement of adjacent high-voltage line towers along the line is inconsistent, the conductor tension and span of adjacent high-voltage line towers will increase relative to one side and decrease relative to the other side. The unbalanced tension generated by span change in adjacent spans will also cause the suspension string to deflect to the side of conductor tension. If the horizontal movement of the foundation on both sides of the high-voltage line tower is inconsistent, not only the above problems will occur, but also the root opening of the high-voltage line tower foundation will increase or decrease. The change of the root opening will cause additional stress in the structure of the high-voltage line tower, especially near the transverse plane near the foundation at the lower part of the high-voltage line tower, the stress is the largest, which is very easy to cause bending or even damage to the transverse bar.

The superstructure load acts on the foundation vertically without considering the effect of horizontal load. This is because the horizontal stress on the foundation caused by the horizontal deformation of the ground surface is certain and will not exceed the friction between the foundation and the foundation. When the friction is greater than the friction between them, the foundation and foundation slide, and the stress is no longer transmitted upward. In other words, for buildings with combined foundation, the superstructure will not be subject to additional stress caused by horizontal deformation of the ground surface. However, for the high-voltage line tower structure with independent foundation, if the horizontal movement of the independent foundation is inconsistent, the superstructure will bear tension or compression and generate additional stress in the structure. Therefore, the horizontal movement and deformation of the independent foundation can be transferred to the superstructure through the foundation. Therefore, the independent foundation of truss structure such as high-voltage line tower not only transfers the load in the vertical direction, but also transfers the load in the horizontal direction. For the independent foundation, it is necessary to study the influence of its horizontal load.

4. Summary
According to the analysis, the relationship between the maximum compressive stress, the maximum tensile stress, the inclination of the tower and the surface inclination deformation is obtained.

At a certain inclination value, the maximum axial compressive stress of the high-voltage line tower is located at the position of the main material of the leg at the relative fixed side of the tower, and the maximum
tensile stress is located at the position of the inclined material of the leg of the high-voltage line tower. With the increase of the surface inclination, the axial compressive stress of the compression bar and the axial tensile stress of the pull rod also increase. There is a quadratic nonlinear relationship between the maximum compressive stress of the member and the surface tilt deformation. With the increase of the surface tilt, the maximum compressive stress of the member increases monotonically. The maximum axial tensile stress of the member shows a quadratic nonlinear monotonic increasing trend with the increase of the surface inclination.

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