

Research on Anti-Foundation-Displacement Performance and Reliability Assessment of 500 kV Transmission Tower in Mining Subsidence Area

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Abstract: The performance of resisting foundation displacement of typical single return circuit and double return circuit transmission towers under all kinds of load conditions including foundation horizontal displacement, foundation vertical uneven downward displacement were analyzed by finite element modeling. Results showed that stability failure of single steel angle represents tower's limit state under foundation displacement. The corresponding foundation displacement limits were calculated. And the towers' reliability were assessed by comparing the calculated earth surface deformation in advance to the towers' earth surface deformation permissibility. Result indicates that tower does not fail when foundation displacements are smaller than 0.5% of tower root distance. The assessment result revealed that under coal mining deformation conditions, complex foundation and measures adjusting the length of bolts between towers' legs and foundations can ensure all object towers' safety. The complex foundation is more effective than single foundation in resisting coal mining deformation.

Keywords: Mining subsidence area, electricity transmission tower, limit state, single return circuit, double return circuit, anti-foundation-displacement performance, 500 kV, reliability assessment.

1. INTRODUCTION

Power transmission line is the lifeline engineering for China's economic development and social stability. With the rapid development of China's electric power construction, more and more high-voltage and extra high-voltage transmission lines have to be installed in mining subsidence areas of coal mines for example, there a 98.1 km line of "Jingdongnan-Nanyang-Jingmen 1000 kV alternating current transmission line" which is the first UHV transmission line of China, lie above coal mining subsidence area of Shanxi Province and Henan Province, [1] and there are many other 110 ~ 500 kV lines in Neimenggu Province and Jiangsu Province facing the problems of coal mining [2-9]. The transmission towers above the coal mining subsidence will be facing the damage by the whole foundations' uniform vertical displacement, foundations' respective uneven vertical displacement, foundations' incline, foundations' relative horizontal displacement. Therefore it is quite possible that either the tower's structure will be destroyed, or the tower's deformation and displacement will be too large to ensure the function of transmission line. Keeping in view the stress status, failure mechanism and safety assessment of transmission tower within coal mining subsidence area are the issues that should be focused on.

At present, the specifications and regulations still lacks the recommendations for reference, which is related to the limited mining surface deformation the transmission tower could bear and its safety assessment [12-16]. Previous studies have focused on the deviation rectifying and supporting the tower base, foundation reinforcement, improvement of foundation type, and control of mining methods, etc. [2-9, 17], while the research on the properties of transmission tower within the coal mining subsidence area resisting the limited mining surface deformation are very few, [11, 18, 20] and the research on the safety assessment of transmission tower within coal mining subsidence area are even fewer [10]. Reference [10] by using the material yield of tower's Q235 steel as the limit state for tower suffering surface deformation, gives a reliable evaluation method for the transmission tower within coal mining subsidence area. However, the local yield of materials under most working conditions does not indicate the losses of overall resistance of structure therefore, this assessment method is too conservative. For this reason further research on safety assessment method for transmission tower under mining deformation is very important for planning of the transmission line within subsidence area, as well as design and protection of the transmission towers.

In this paper, the research was made on the resistance properties of surface deformation of a typical 500 kV transmission tower under various design conditions. The criterion for unstable failure of a typical bar was proposed to judge whether the tower is destructed. The corresponding

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limit displacement of the tower bearing and the converted surface deformation were obtained to convert surface deformation as the allowable value of surface deformation, which can be endured by the transmission tower within the coal mining subsidence area. An assessment method was proposed to compare the allowable value with the predicted value of surface deformation to determine the safety of tower. Meanwhile, the engineering applications were made in the 500 kV transmission lines of Xulian transmission project.

2. FEA METHOD FOR TOWER

2.1. Establishment of Finite Element Model

This paper chooses three straight line towers as the study objects which are parts of typical 500 kV transmission line. The main parameters of the towers are shown in Table 1. The material of main angle steel is Q345 steel. The material of tilt angle and secondary angle is Q235 steel.

This paper ANSYS Finite Element (FE) software is used to set up a hybrid tower model of beam and link element [19]. BEAM188 element is used to simulate the main angle and crossing tilted materials. The unit has the capability to pull, press, bend, cut, and twist, and to conduct large deformation analysis, to achieve unilateral constraint of end node, and also to make the direction of the angle steel in the model fully in accordance with the actual structure, in order to reduce the calculation error to the maximum extent. Taking the contribution of auxiliary materials to the whole structure into consideration, and LINK 180 element are used to simulate when modeling, and only the pull and press capabilities are considered. For the binding bolts between crossing tilted materials, node coupling function is adopted to make linear displacements in X, Y, Z directions being fully identical, but rotation constraint is not taken into consideration. The finally established FE models of the towers are shown in Fig. (1).

2.2. Exertion of Surface Deformation and Load Working Condition

The foundation displacement of the tower is implemented by exerting corresponding linear displacements on the four foundation nodes, A, B, C, D, respectively, which are placed on the tower base, and the rotation of the tower is constrained. Since this paper focuses on the static analysis, and the unbalanced tension of the wires caused by limited incline is relatively small, therefore the coupling effect of tower-wire system is not taken into consideration, instead, the corresponding loads of the conductor and ground wires are directly applied on the corresponding nodes of the tower.

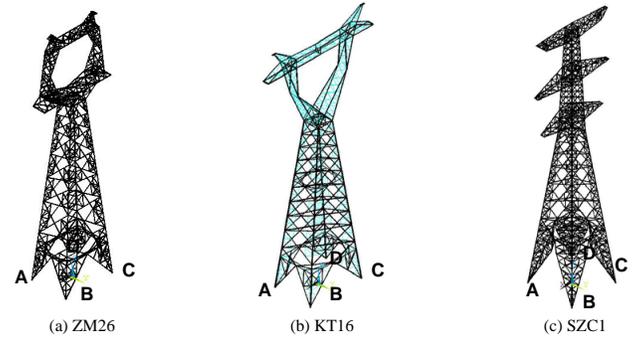


Fig. (1). Finite element model of transmission towers.

In the analysis the foundation displacement under normal conditions (hereafter called single displacement condition for short) is considered, the value of the main working conditions is shown in Table 2, and the single and complex displacement working conditions are shown in Table 3. In Table 3, transverse means the running direction of the line, and longitudinal means the direction perpendicular to the line.

2.3. The Criteria for Judging Limiting Status of Tower Foundation Displacement

This paper takes full advantages of FEA, and takes into account the geometric nonlinearity and material nonlinearity, and conducts fine simulation analysis on the whole process of the transmission tower from being subjected to forceful damage. Through the analysis of the axial force-deflection of typical frame members, unstable member is finally determined and the status when the member it is unstable is regarded as the limiting status of the tower under the action of foundation displacement, and corresponding foundation displacement is the limiting displacement.

3. SUPPORT DISPLACEMENT LIMIT OF TOWERS

This paper analyzes the deformation law of the tower under the force exerted in 11 working conditions listed in Table 3. The results are shown in Figs. (2-7).

3.1. Result of Single Return Circuit Transmission Tower ZM26 and KT16

Using the above mentioned method 11 kinds of single displacement conditions in Table 3 are analyzed, the obtained corresponding foundation displacement limiting values of ZM26 are shown in Fig. (2). Since in both DLSHU and DNSHU conditions instability of frame members has not appeared, therefore the displacement values are not listed.

Table 1. Main Parameters of the Towers

Towers		Height/m	Foot Distance/m		Electrical Wire Load/kN	Ground Wire Load/kN
single return circuit transmission tower	ZM26	36	7.58	10.37	60.55	5.11
	KT16	54	9.40	13.66	79.07	6.76
double return circuit transmission tower	SZC1	42	13.06	13.06	37.85	6.96

Table 2. Illustration of Load Condition

Item	Temp./	Wind Speed/m/s	Icing Thickness/mm
Max. wind speed	-5	30	0
Max. icing	-5	10	10
Normal conditions	15	0	0

Table 3. Cases of Single Foundation Displacements

Single Displacement Condition	Called for Short
Single foundation longitudinal horizontal pull	SLLA
Single foundation longitudinal horizontal press	SLYA
Single foundation transverse horizontal pull	SNLA
Single foundation transverse horizontal press	SNYA
Single foundation vertical sink	SSHU
Double foundation longitudinal of horizontal pull	DLLA
Double foundation longitudinal horizontal press	DLYA
Double foundation transverse horizontal pull	DNLA
Double foundation transverse horizontal press	DNYA
Double foundation longitudinal vertical sink	DLSHU
Double foundation transverse vertical sink	DNSHU

It can be seen from Fig. (2) that when the ZM26 tower is subject to vertical deformation action of the surface its capability to resist press deformation is higher than that to resist pull deformation. For example, in single foundation longitudinal horizontal displacement condition the limiting displacement of SLLA is 145 mm, and for SLYA is 161 mm, the latter is about 11.3% larger than the former. In double foundation longitudinal horizontal deformation condition the limiting displacement of DLLA is 148 mm, and for DLYA being 156 mm, the latter is about 1.0% larger than the former. It is mainly attributed to the difference of the stress status of the wide plane inner crossing tilted angle resulted from the pull and press actions, that is, under pull action the unstable frame members are the wide plane (AD plane and BC plane) first crossing tilted angles, while under press action the unstable frame members are the wide plane second crossing tilted angles, have a same cross-section, but the first crossing length is larger than the second, therefore it has a few litter unstable critical load.

Fig. (3) shows the ratio of ZM26 limiting displacement under various conditions to the corresponding root distance. Of which the ratio in SSHU condition corresponds to the root distance in length direction. It can be seen from Fig. (3) that the limiting displacement of the tower foundation under pull condition is 1.26 to 1.43% of the corresponding root distance, and the limiting displacement under press condition is 1.36 to 1.55% of the corresponding root distance, the limiting displacement under single foundation sink condition

is 0.54% of the length direction root distance. As a result, if the foundation displacement is smaller than 1.25% (pull condition and press condition) and 0.50% (single foundation sink condition) of the corresponding root distance, the tower will not undergo unstable damage.

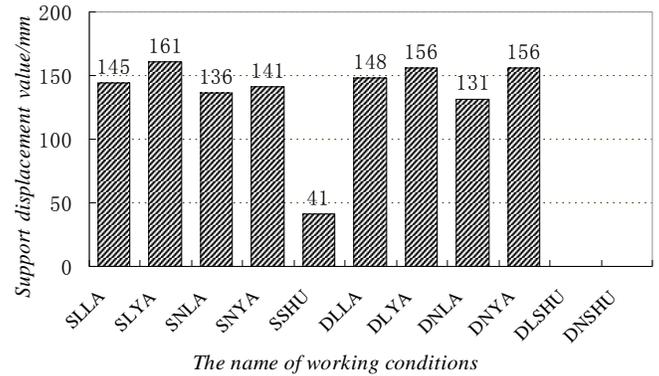


Fig. (2). Support displacement limit under single foundation displacements cases

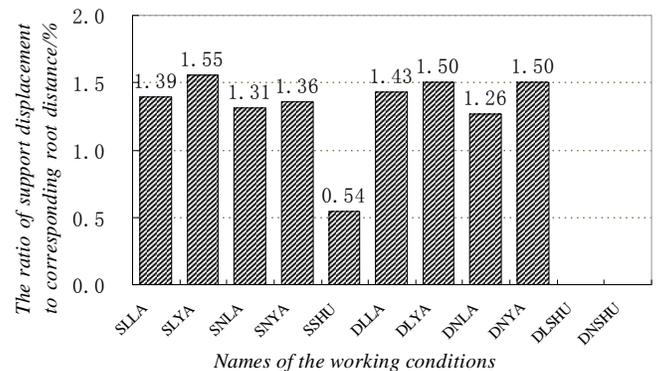


Fig. (3). The ratio of limiting foundation displacement to corresponding root distance

The support displacement limit and the ratio of tower KT16 are shown in Figs. (4 and 5), respectively.

It can be seen from Fig. (4) that when the tower KT16 is subject to vertical deformation action of the surface its capability to resist pull deformation is significantly higher than that to resist press deformation. For example in single foundation longitudinal horizontal displacement condition the limiting displacement of SLLA is 171 mm, and for SLYA is 86 mm, the former is about twice of the latter; and in double foundation longitudinal horizontal deformation condition the limiting displacement of DLLA is 181 mm, and for DLYA is 116 mm, the former is about 1.6 times of

the latter. It is mainly attributed to the difference of the stress status of the wide plane inner crossing tilted angle steel resulted from the pull and press actions, that is, under pull action the unstable frame members are the wide plane (AD plane and BC plane) first crossing tilted angle steel (L140×10), while under press action the unstable frame members are the wide plane second crossing tilted angle steel (L90×7), the length of them differs less, but the former has a much large cross-section, therefore it has a much larger unstable critical load.

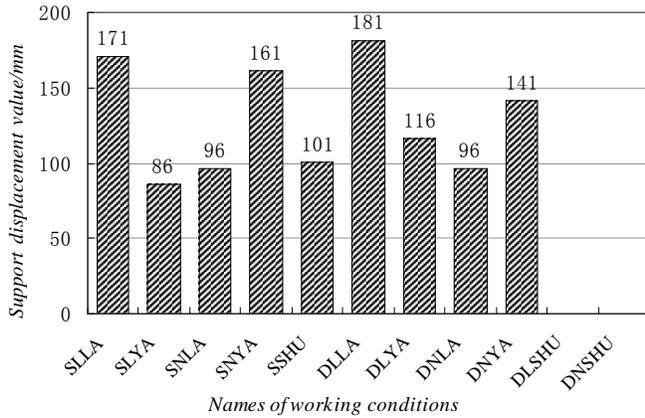


Fig. (4). Support displacement limit of KT16 under single foundation displacements cases.

In the same time when the tower KT16 is subject to surface transverse deformation action its press deformation resistance is significantly higher than its pull deformation resistance. For example, in single foundation transverse horizontal displacement condition the displacement of SNYA is 161 mm, and for SNLA is 96 mm, the former is about 1.7 times of the latter; and in double foundation transverse horizontal deformation condition, the displacement of DNYA is 141 mm, and for DNLA is 96 mm, the former is about 1.47 times of the latter. The reason is similar within the longitudinal conditions: for narrow plane (AB plane and CD plane) both the first and second crossing tilted angle steel are L90×7, but the former is longer, therefore the critical load for the second tilted angle steel is much larger, leading to the result of in press condition stronger than in pull condition.

Fig. (5) shows the ratio of KT16’s limiting displacement under various conditions to the corresponding root distance. Of which the ratio in SSHU condition corresponds to the root distance in length direction.

It can be seen from Fig. (5) that the KT16’s limiting displacement of the tower foundation under pull condition is 1.02 to 1.33% of the corresponding root distance, and the limiting displacement under press condition is 0.63 to 1.71% of the corresponding root distance, the limiting displacement under single foundation sink condition is 0.74% of the length direction root distance.

As a result if the foundation displacement is smaller than 1.0% (pull condition) and 0.5% (press condition and single foundation sink condition) of the corresponding root distance, the tower will not undergo unstable damage.

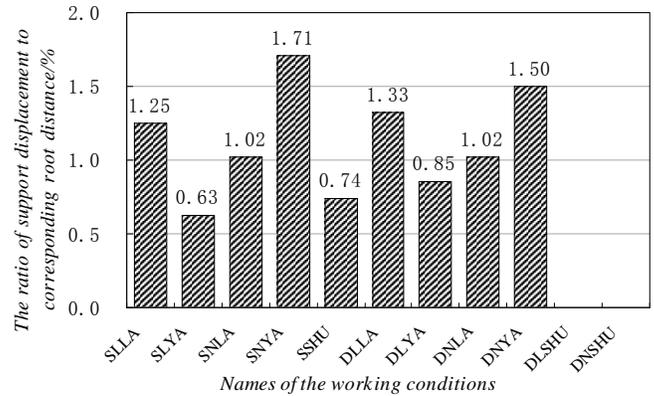


Fig. (5). The ratio of KT16’s limiting foundation displacement to corresponding root distance.

3.2. Result of Double Return Circuit Transmission Tower SZC1

The support displacement limit and the ratio of tower SZC1 are shown in Figs. (6 and 7), respectively.

It can be seen from Fig. (6) that when the tower is subject to vertical deformation action of the surface its capability to resist press deformation is higher than that to resist pull deformation. For example, the limiting displacement of SLLA is 202 mm, and for SLYA is 227 mm, the latter is about 12.3% larger than the former; and the limiting displacement of DLLA is 227 mm, and for DLYA is 277 mm, the latter is about 22% larger than the former. It is mainly attributed to the difference of the stress status of the wide plane inner crossing tilted angle resulted from the pull and press actions, that is, under pull action the unstable frame members are the first crossing tilted angles on the AD plane and BC plane, while under press action the unstable frame members are the wide plane second crossing tilted angles, have the same cross-section, but the first crossing length is larger than the second, therefore it has a few litter unstable critical load.

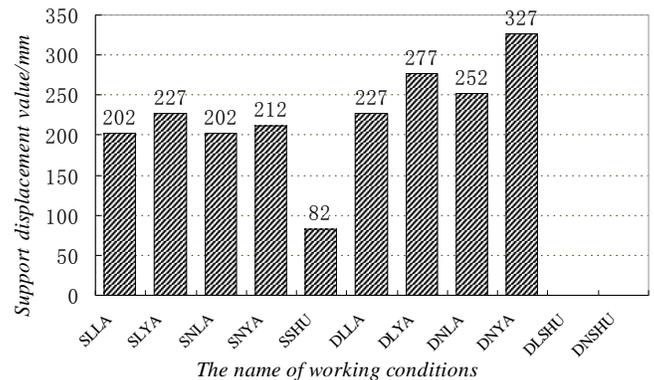


Fig. (6). Support displacement limit under single foundation displacements cases.

Fig. (7) shows the ratio of limiting displacement under various conditions to the corresponding root distance. Of which the ratio in SSHU condition corresponds to the root distance in length direction. It can be seen from Fig. (3) that the limiting displacement of the tower foundation under pull

condition is 1.55 to 1.93% of the corresponding root distance, and the limiting displacement under press condition is 1.62 to 2.50% of the corresponding root distance, the limiting displacement under single foundation sink condition is 0.63% of the length direction root distance.

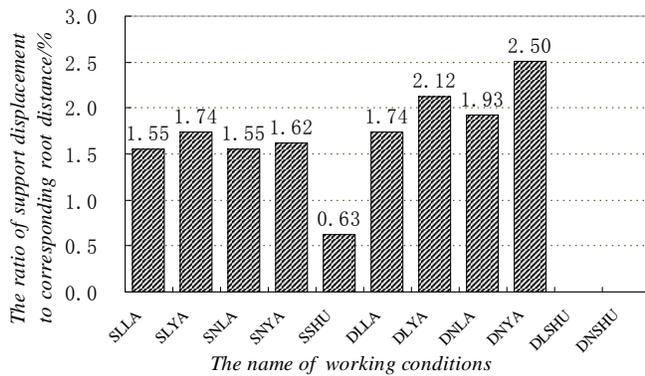


Fig. (7). The ratio of limiting foundation displacement to corresponding root distance.

As a result, if the foundation displacement is smaller than 1.50% (pull condition and press condition) and 0.50% (single foundation sink condition) of the corresponding root distance, the tower will not undergo unstable damage.

4. RELIABILITY ASSESSMENT OF TOWERS

4.1. Assessment Method

Before assessment, this paper firstly got the equivalent earth surface deformation by dividing the limiting support displacement with the corresponding root distance, and taking the minimum as the earth surface deformation permissibility (Δ_u). On the contrary, Δ is taken as a sign of the calculated earth surface deformation in advance by probability integral forecast modeling. Forecast results show that there are more than 45 towers which will face the damage from the coal mining subsidence. The main forecast deformation when all the coal beds is mined are shown as follow: maximum subsidence is 3291 mm, maximum incline is 14 mm/m, maximum horizontal deformation is 7.1mm/m, maximum curvature is 0.101 mm/m² [20]. Therefore, it is considered that the tower will be safe only if its Δ is less than

the corresponding Δ_u . The reliability of all ZM26 and KT16 towers of the object transmission line is assessed by this method.

The above discussion is based on the primary design of the towers with single foundations. If the assessment shows unsafe result at some towers, then a design of complex foundation will be introduced to make a new assessment [18, 20]. According to the results of reference [18], the Δ of horizontal deformation and curvature deformation are discounted at 40 % and 20%, respectively.

4.2. Assessment Result of Tower ZM26 and KT16

The main assessment result of ZM26 and KT16 of the object transmission line is shown in Table 4.

Table 4 here

It can be seen from Table 4 that all the incline Δ are larger than the corresponding Δ_u . But it can be overcome by adjusting the length of bolts between towers' legs and foundations. Therefore, all the ZM26 towers are safe. The forecast horizontal deformation of KT16 with single foundation is larger than its Δ_u , which means that single foundation can not satisfy all requirements of anti-deformation. On the contrary, KT16 towers with complex foundation are safe.

In conclusion under coal mining deformation conditions, complex foundation and measures adjusting the length of bolts between towers' legs and foundations can ensure all ZM36 and KT16 towers' safety.

CONCLUSIONS

- (1) The limiting status of the tower under the action of foundation displacement is characterized by the instability of the crossing tilted angle in the vicinity of the bottom transverse diaphragm, therefore, it is necessary to take effective measures to enhance the out-plane stiffness of the bottom crossing tilted angle.
- (2) When the foundation displacement is smaller than 0.50% of the corresponding root distance, respectively, the transmission tower according to this paper will not occur unstable damage.

Table 4. Influence of Surface Deformation to Reliability of Transmission Tower When all of the Coal Beds were Mined

Items		ZM36	KT16 (Single Foundation)	KT16 (Complex Foundation)
Single foundation vertical sink	Δ	5.7	6.9	6.9
	Δ_u	61	101	101
Incline / mm•m ⁻¹	Δ	14	14	14
	Δ_u	5	5	5
Horizontal deformation / mm•m ⁻¹	Δ	7.1	7.1	4.26
	Δ_u	7.17	5.90	5.90
Curvature deformation / mm••m ⁻²	Δ	0.10	0.10	0.08
	Δ_u	1.18	1.69	1.69
Assessment result		safe	unsafe	safe

- (3) Under coal mining deformation conditions, complex foundation and measures adjusting the length of bolts between towers' legs and foundations can ensure all ZM36 and KT16 towers' safety.
- (4) The conclusions of this paper is obtained on the basis of the FEA on specific single return circuit tower, its applicability should be further studied on other types of towers.

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