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RESEARCH ARTICLE

Study on the Effect of Bolt Slippage and Foundation Settlement on the Bearing Capacity of Tower-Line System

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ABSTRACT The bolted joints of angle steel transmission tower will slide relatively under load, that is, the bolt-slippage effect. The existing research on the bearing capacity of transmission towers often ignores the bolt-slippage effect, resulting in deviations in the analysis of the bearing capacity of transmission towers. To evaluate the bearing capacity of transmission tower more accurately, the finite element model of transmission tower considering bolt-slippage effect and the finite element ideal rigid frame model of transmission tower without considering bolt-slippage effect are established. The distribution and stress changes of failure members of the two models under static wind load and longitudinal unbalanced tension caused by uneven icing and wire breakage under different settlement modes and settlement amounts are calculated. The difference of bearing capacity between the two models is compared and analyzed, and the influence of bolt slippage and foundation settlement on the two models is obtained. The results show that the bolt-slippage effect will significantly increase the deformation and displacement response of the transmission tower, and at the same time affect the stress distribution of the members, resulting in the failure position and failure mode of the members of the two models are not exactly the same. Ignoring the bolt-slippage effect will overestimate the bearing capacity of the transmission tower-line system. The bolt-slippage effect makes the bearing capacity of the tower-line system decrease more slowly with the settlement. To calculate the bearing capacity of the tower-line system more accurately, the bolt-slippage effect cannot be ignored.

INDEX TERMS Bolt slippage, foundation settlement, transmission tower.

I. INTRODUCTION

The reliable and secure operation of transmission lines is crucial in the power transmission process. The angle steel transmission towers are connected by bolts. The diameter of the bolt hole is usually larger than that of the bolt rod, creating a gap between the rod and the hole. This gap causes relative sliding between the two under external forces, which is known as bolt slippage. Currently, research on bolt slippage has yielded significant results both domestically and internationally. Ungkurapinan et al. [1], [2] proposed a mathematical model that describes the load–displacement relationship of a single bolt through testing. Ahmed et al. [3] conducted a static nonlinear analysis using this mathematical model to investigate the impact of freezing and expansion on a tower's mechanical response. The results showed that the axial force of the bar, considering bolt slippage, is less than that of the bar without considering bolt slippage. Additionally, the axial force of the bar without considering bolt slippage is less than that of the bar without considering bolt slippage. It is important to note that the content of the improved text must be as close as possible to the source text, and the addition of further aspects must be avoided at all costs. The results indicate that the axial force of the bar decreases when bolt slippage is not considered. Jiang et al. [4], [5] developed an accurate model of a transmission tower that considers both bolt slippage and initial defects of the bar. Through numerical simulation and full-size testing, it was found that all of these factors affect the

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damage to the transmission tower. Bolt slippage significantly affects the displacement of the tower and the bending damage bearing capacity. Mohammadi et al. [6] proposed a modeling method for transmission towers that considers uncertainties. They analyzed the effect of bolt slippage and showed that it reduces the tower's load-carrying capacity by 6% and significantly increases the tower's top displacement. In their study, Souza et al. [7] simulated the successive collapses of two tower-line systems, one considering bolt slippage and the other not considering bolt slippage. The results indicated that the tower-line system considering bolt slippage had a greater probability of failure. An experiment by An et al. [8] revealed that bolt slippage occurs through a complex process involving elastic deformation caused by frictional load transfer and asynchronous joint slippage. They proposed a generalized joint unit to describe the joint-slippage effect. Li and Zhan [9] considered the effect of the friction surface slip coefficient and improved upon the model presented in the literature [1], [2]. They proposed a joint-slippage model for galvanized steel bolts. However, the studies mentioned above were limited to static calculations. Li et al. [10] investigated the damage modes of K-joints under reciprocating vibration loading through numerical modeling methods. The results showed that the damage modes of the K-joints were related to the bolt grade and steel strength. Li et al. [11] integrated skeleton curves obtained from field tests and numerical simulations into a tower-line system model for seismic analysis. The results showed that neglecting the reciprocating slippage of the bolts underestimates the seismic response of the transmission tower.

Yang et al. [12], [13] analyzed the limit values of foundation deformation for transmission towers using numerical simulation methods. They also analyzed the load bearing capacity of the towers under high wind conditions. The analysis focused on towers with different types of foundation deformations. The study revealed that the foundation deformation limit was the lowest when subjected to 60° wind, and the stress on the main material exceeded 34% of the design value under the design wind speed. Shu et al. [14] conducted a normal condition loading test on a scaled-down model of a transmission tower's horizontal support to determine the deformation and stress of the model, which was then verified using a finite element model. The results indicate that surface deformation had a more significant effect on the truss members located near the supports. Shu et al. [15], [16] developed a finite element model and conducted surface tension and expansion scale tests under different wind load conditions to analyze the deformation resistance of a transmission tower. The study showed that the wind load is the most critical factor in the case of displacement of the foundation in compression or tension and that it has a significant adverse effect on the resistance of the transmission tower under the effect of surface deformation. Wu et al. [17] conducted a numerical investigation into the safety performance of a jacking tower during inhomogeneous foundation settlement in a mining area. The results indicated that the stress change in the transmission tower leg was the most significant.

In summary, the majority of current studies have analyzed the load-carrying capacity of transmission towers in relation to foundation deformation. However, there are few studies that consider the role of bolt slippage, and there is a lack of research on specific loads. This paper presents two transmission tower-line system models, one with bolt slippage and one without bolt slippage. The distribution and stress changes of the damaged members of the transmission tower under wind load and longitudinal unbalanced tension are calculated for different settlement amounts and methods. This study investigated the effects of bolt slippage and foundation settlement on the load carrying capacity of a tower-line system.

II. NUMERICAL MODEL

In this paper, a 2-tower and 3 span tower-line system in a heavy ice area is selected as the object of study, and the tower-line system model is shown in Figure 1. The transmission towers are 500 kV double circuit transmission towers with a height of 99.9 m, a caliper height of 69.0 m and a foundation size of 18 m, and the specific dimensions are shown in Figure 2. The main member of the tower body is Q420 steel, and the diagonal and auxiliary members are Q345 and Q235 steel. The conductor is a four-bundle conductor model LGJ-630/45, the ground wire model is JLB20A-150, and the mechanical parameters of the conductor and ground wire are shown in Table 1. The insulator model is U210BP/170T, and the length is 6.6 m.

TABLE 1. Mechanical parameters of conductor and ground wire.

Parameters	LGJ-630/45	JLB20A-150
Diameter (mm)	33.6	15.75
Weight (kg/m)	2.06	0.9894
Elastic modulus (MPa)	63000	147200
Area (mm^2)	666.55	148.07
Ratedtensile strength (N)	148700	178570
Serviceable strength (N)	35316.25	30535.47

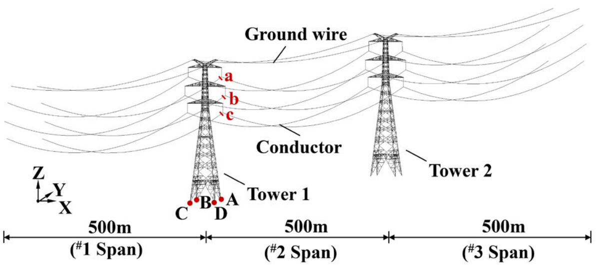


FIGURE 1. Diagram of tower-line system model.

ANSYS software is used to construct the ideal rigid frame tower model (RT) and the tower model considering bolt slippage (JT). The BEAM189 unit is used to model the transmission tower members and each tower leg member is composed

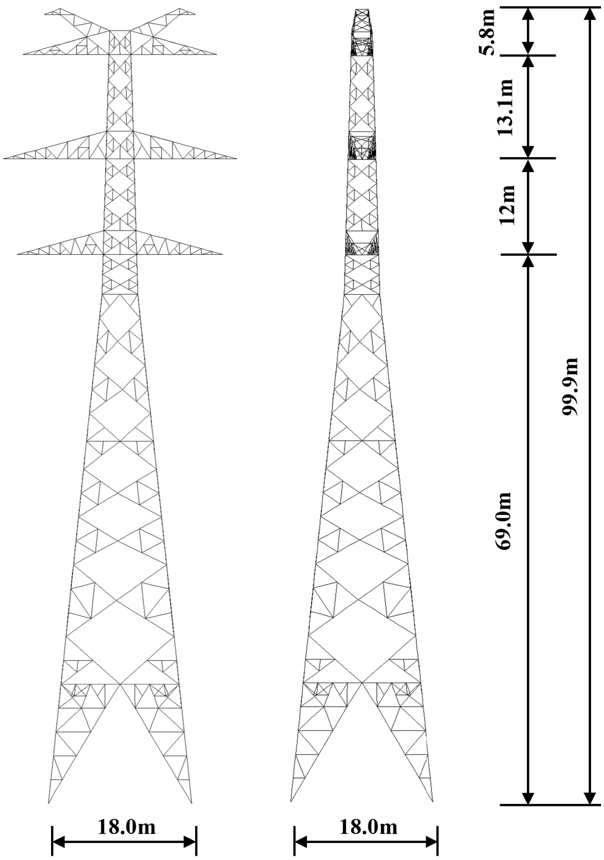


FIGURE 2. Size of transmission single tower.

of three units. The connection nodes between the members of RT are rigid connections. To simulate the bolt slippage action, overlapping nodes are created on the basis of the rigid connection nodes, a zero-length nonlinear spring unit, COMBIN39, along the axial direction of the members is added between the two nodes, and the degrees of freedom of the two types of units are coupled. Finally, the data of the skeleton curve of the bolted connection under cyclic obtained from experiments and numerical simulations are inputted into the spring unit as a real constant to set up the mechanical spring.

The node modeling schematic is shown in Figure 3. The LINK10 unit is used to simulate the conductor, and the LINK8 unit is used to simulate the ground wire. The distal end of the conductor is connected as an articulated joint. The steel constitutive relationship adopts the multilinear follower reinforcement model shown in Figure 4 [11]. σ_y represents the yield stress, σ_u represents the ultimate stress, ε_y represents the yield strain, and ε_u represents the ultimate strain. Poisson ratio is 0.3.

III. ANALYSIS OF WIND LOAD CARRYING CAPACITY OF TOWER-LINE SYSTEM

A. WIND LOAD SIMULATION METHODS AND WORKING CASES

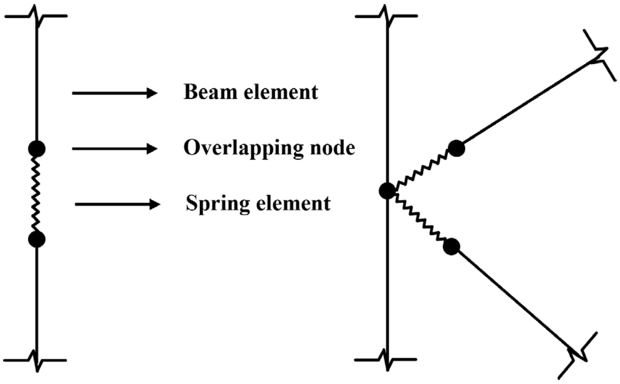


FIGURE 3. Diagram of joint model.

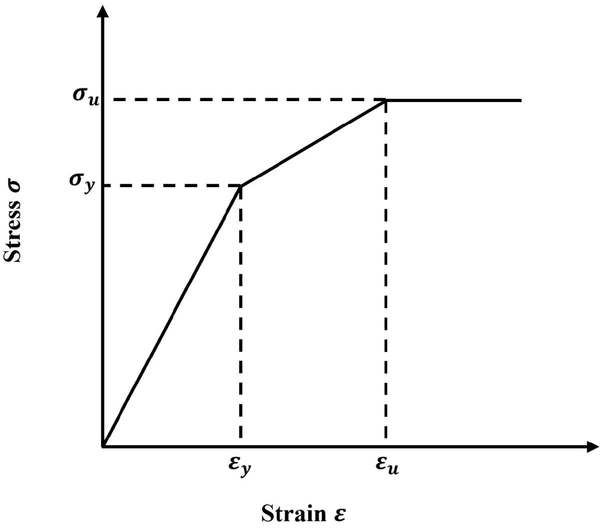


FIGURE 4. Constitutive relation.

Figure 5 shows that the transmission tower is divided into 14 regions, with each region represented as a simulation point. The wind load is applied as a concentrated load, and the tower wind load is applied to the tower node at the height of the simulation point. The wind load borne by the conductor and ground wire is applied to the node of the wires.

According to the Chinese code 'Technical code for the design of tower and pole structures of overhead transmission line' (DL/T 5154-2012) [18], the standard wind load on the pole tower is calculated via (1) and (2):

$$W_s = W_0 \cdot \mu_z \cdot \mu_s \cdot B_2 \cdot A_s \cdot \beta_z \tag{1}$$

$$W_0 = V^2/1600 \tag{2}$$

where W_s is tower wind load standard value (kN), μ_s is member of the body type coefficient, the tower to take $1.3(1+\eta)$, B_2 is tower member icing wind load increase coefficient, A_s is windward side of the projected area of the members of the value (m^2), η is tower leeward side of the load reduction factor, β_z is tower wind load adjustment coefficient, W_0 is base wind pressure standard value (kN/m^2); and V is base height of 10m wind speed (m/s).

This paper investigates the impact of bolt slippage and foundation settlement on the bearing capacity of

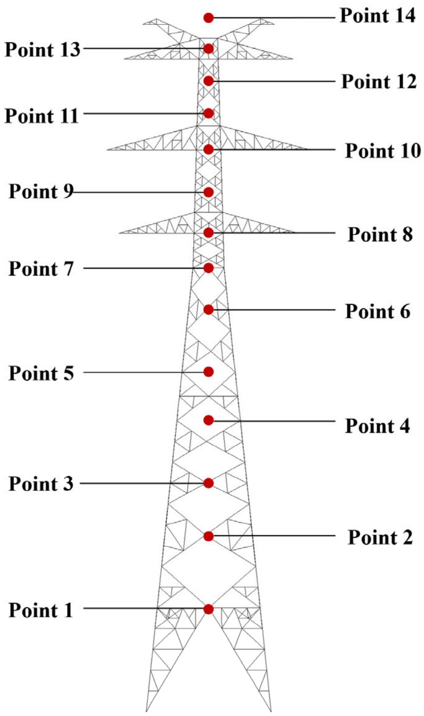


FIGURE 5. Transmission tower wind speed simulation point.

transmission tower-line systems. Specifically, the influence of static wind loads on the bearing capacity of transmission towers is examined for both RT and JT. This study considers different foundation settlements of 0m, 0.025m, 0.05m, and 0.075m for tower 1. The connection between the bearing and the tower is considered to be rigid. To simulate the foundation settlement of the transmission tower, a displacement load is applied to the tower foot node. The wind direction is static and in the +X direction, perpendicular to the conductor. Table 2 shows the foundation settlement conditions under a wind load.

TABLE 2. Foundation settlement cases under wind load.

Case No.	Deformation category	Description
A0	No foundation settlement	Foundation not settling
A1	One foundation settlement	Foundation A
A2	Two foundations settlement	Foundation A and B
A3	Three foundations settlement	Foundation A, C, and D

B. ANALYSIS OF WIND LOAD CARRYING CAPACITY OF TOWER-LINE SYSTEM WITH FOUNDATION SETTLEMENT

The tower top displacement serves as the ultimate performance evaluation index [19]. To evaluate the RT and JT, Pushover analysis was performed under a static wind load during foundation settlement. The tower top displacement collection points are shown in Fig. 6, and the corresponding calculation results for both models for cases A0-A3 are given in Table 3. The tower top displacement curves for the A0 and A1 cases under static wind loading are presented in Figure 7.

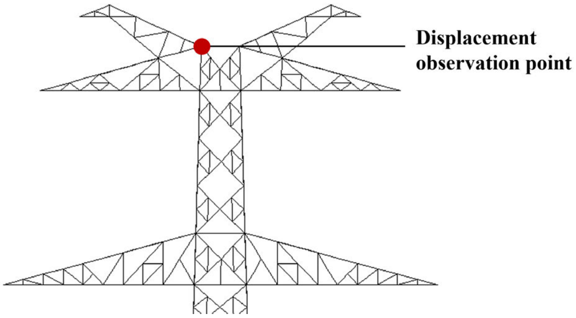


FIGURE 6. Diagram of joint model.

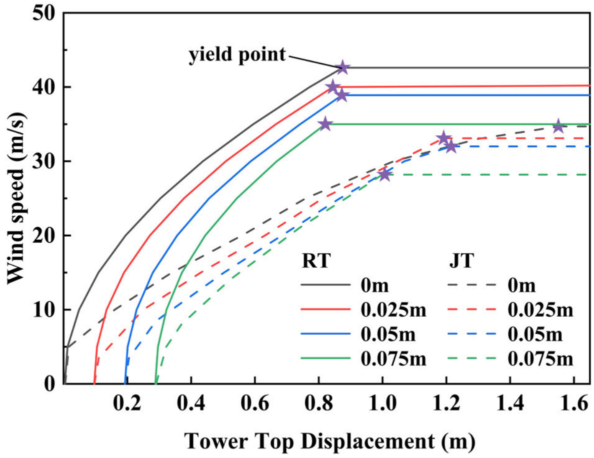


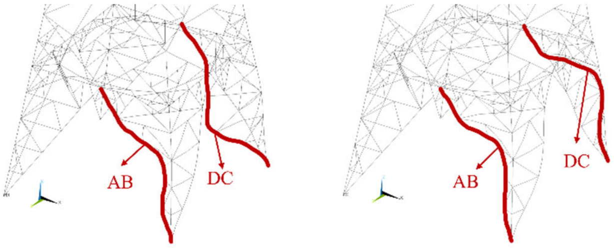
FIGURE 7. Tower top displacement under wind load.

TABLE 3. Extreme wind and failure members of various cases under wind load.

Case No.	Settlement (m)	Extreme wind (m/s)		Failure member	
		RT	JT	RT	JT
A0	0	42.6	34.7	AB、DC	AB、DC
A1	0.025	40	33.1	AB、DC	AB、DC
	0.05	38.9	32	DC	DC
	0.075	35	28.2	DC	DC
A2	0.025	42.2	33.9	AB、DC	AB、DC
	0.05	41.8	32.8	AB、DC	AB、DC
	0.075	40.5	32.5	AB、DC	AB、DC
A3	0.025	40	33.5	AB、DC	AB、DC
	0.05	38.6	32.2	DC	DC
	0.075	35.3	30.5	DC	DC

Both the RT and JT experience deformation in the downwind direction. However, the RT experiences greater deformation due to the bolt-slippage effect. Figure 7 shows that the tower top displacement of JT is 3.3 times greater than that of RT. When there is no foundation settlement, the top displacement of RT is 0.19 m under a wind speed of 20 m/s, while the top displacement of JT is 0.56 m. Neglecting the bolt-slippage effect will seriously underestimate the displacement response of the tower under the action of static wind loads. This greatly affects the safety of transmission tower, as indicated by the fact that when the top displacement of RT reaches 0.56 m, the wind speed approaches 35 m/s.

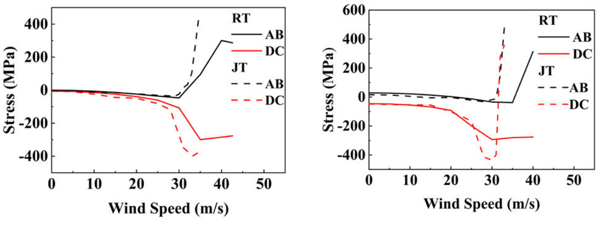
For case A1 foundation settlement of 0.025 m, both RT and JT exhibited obvious buckling of the AB and DC members at their respective limiting wind speeds, resulting in their destruction. Figure 8 shows the location and mode of damage for the affected members in both RT and JT. For member DC, the stiffened tower member flexes toward the tower interior, while JT member flexes toward the tower exterior. This is due to the combined effect of the stresses generated by the larger tower top displacement and the additional stresses on the tower legs generated by foundation settlement. It is important to note that the two damage modes are not the same. The stress distribution of the rods in the foundation settlement transmission tower is affected by the bolt slippage, which in turn affects their damage modes.



(a) RT (b) JT

FIGURE 8. **Failure members under wind load (Amplify deformation by 10 times).**

Figure 9 shows the stress changes in the failure members under case A0 and A1-0.025 m. The figure shows that under the case A0, member AB and DC experienced wind speeds of 30 m/s and 28 m/s, respectively. The stress increased rapidly, and JT exhibited a significantly faster growth rate than did RT. Subsequently, the members in both models reached the extreme stress value and were destroyed. However, they still had a load-bearing capacity to continue carrying the load and ultimately entered the plastic phase. The stress decreased until it reached the extreme wind. The member fails completely. For member AB in case A1-0.025 m, the stress of JT and RT damage member starts to increase rapidly at 30 m/s and 35 m/s, respectively. The growth rate of JT failure member stress is obviously greater than that of RT. For member CD, both stress levels start to increase at the same time when reaching 20 m/s. However, the stress growth rate of the damaged member in JT is significantly greater than that in RT. Additionally, both members fail simultaneously in JT, which is not the case for RT. It is worth noting that both members fail faster in JT. The stress change of the failure members is greater when settling 0.025 m than when not settling. Consequently, the bearing capacity of the transmission tower-line system decreases more rapidly under static wind loading when considering the bolt-slippage effect. Neglecting the bolt-slippage effect leads to an overestimation of the bearing capacity of the tower-line system in this case.

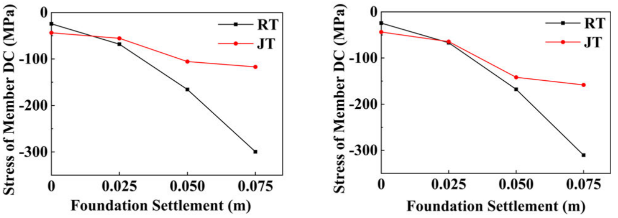


(a) Case A0 (b) Case A1-0.025m

FIGURE 9. **Relationship between stress of failure members and wind speed under wind load.**

C. EFFECT OF BOLT SLIP AND FOUNDATION SETTLEMENT ON WIND LOAD CARRYING CAPACITY OF TOWER-LINE SYSTEM

Figure 7 shows that at a wind speed of 20 m/s under the case A0, the top displacement of RT is 0.19 m due to bolt slippage action, while the top displacement of JT is 0.56 m. The bolt slippage action increases the top displacement by 188%. The top displacement of RT is 0.44 m for the case A1-0.075 with only foundation settlement at the same wind speed. The displacement of the top of the tower increased by 128% due to foundation settlement, which is smaller than the increase in the displacement of the top of the transmission tower caused by the action of bolt slippage alone. Under static wind loading, bolt slippage has the greatest effect on the deformation of the transmission tower. Ignoring this action will overestimate the safety performance of the tower, making it imperative to consider it.



(a) Case A1 (b) Case A3

FIGURE 10. **Stress variation of member DC under 15m/s wind speed.**

Figure 10 shows the stress variation of the failure member DC in RT and JT as the settlement changes under a wind speed of 15 m/s under case A1 and A3. The stress change amplitude of RT member is larger and grows faster than that of JT as shown in the figure. At a settlement of 0.075 m, the stress in RT member reached 2.56, which is 1.96 times that of JT and closer to the ultimate stress of the member. Ignoring the bolt-slippage effect will result in an underestimation of settlement when damage occurs, which can affect the accurate assessment of the bearing capacity of a tower-line system under static wind loads. Therefore, it is important to consider the bolt-slippage effect to ensure a more gradual decrease in the system's bearing capacity.

IV. ANALYSIS OF LONGITUDINAL UNBALANCED TENSION BEARING CAPACITY OF TOWER-LINE SYSTEM

The transmission tower-line system consists of a transmission tower, conductor, ground wire, insulators, and other coupling system parts. The system operates in a state of equilibrium where each part is under tension. Severe weather conditions, such as freezing rain and blizzards, can cause the tower-line system to experience inhomogeneous ice covering and wire breakage. These phenomena can result in excessive longitudinal unbalanced tension, leading to the breakdown of the tower-line system's equilibrium state and potentially causing serious accidents, such as tower collapse [20]. This paper analyses the longitudinal unbalanced tension conditions caused by inhomogeneous ice cover and wire breakage.

A. WIND LOAD SIMULATION METHODS AND WORKING CASES

1) INHOMOGENEOUS OVERLYING ICE LOAD SIMULATION AND WORKING CASES

To simulate the guide wire ice-covering load, the changing density method is used by increasing the density of each wire and converting the ice-covering load into the longitudinal load of the wire itself. The equivalent density of the guide line ice cover is calculated using (3) [21]. According to the Chinese code 'Technical code for design overhead transmission line in medium-heavy icing areas'(Q/GDW 10182-2017) [22], the thickness of the ice cover on the ground wire should be increased by 5 mm compared to that of the conductor. This ensures the equivalent density of the conductor and ground wire under different ice cover thicknesses.

$$\rho' = \frac{w_1 + w_2}{A} \tag{3}$$

where ρ' is equivalent density with ice cover (kg/m^3), w_1 is self-weight of conductor (kg/m), w_2 is ice-cover weight (kg/m), A is cross-sectional area of conductor (m^2).

According to the Chinese code ' Standard for design of high-rising structures' (GB 50135-2019) [23], (4) provides a formula for calculating the longitudinal load on the ice cover of noncircular cross-sectional components per unit area of the tower body. The tower body ice-covering load per section of the transmission tower under different ice-covering thicknesses is calculated by determining the total surface area of the bars in each section of the transmission tower, as shown in Figure 5. This load is then applied to the tower nodes at the height of the simulation point in the form of a centralized load.

$$q_\alpha = 0.6b\alpha_2\gamma \times 10^{-3} \tag{4}$$

where q_α is longitudinal load of ice cover per unit area (kg/m^2), b is basic ice thickness (mm), α_2 is height increment factor for ice cover thickness, γ is force density of ice, usually 9kN/m^3.

Inhomogeneous ice-covering cases are simultaneously calculated based on the unbroken line, inhomogeneous ice, -5°C, and a wind speed of 15 m/s (+X direction). Assuming that the thickness of the tower body ice cover is 20 mm, the thicknesses of the #1 span and #3 span guide line ice cover are 20 mm, and the thickness of the #2 span guide line ice cover is changed. This study considers models of RT and JT with different foundation settlements of 0m, 0.025m, 0.05m, and 0.075m and analyzes the impact of longitudinal unbalanced tension caused by inhomogeneous ice cover on the bearing capacity of tower 1. Table 4 displays the foundation settlement cases during inhomogeneous ice cover.

TABLE 4. Foundation settlement cases of inhomogeneous icing.

Case No.	Deformation category	Description
B0	No foundation settlement	Foundation not settling
B1	One foundation settlement	Foundation A
B2	Two foundations settlement	Foundation A and B
B3	Three foundations settlement	Foundation A, B, and D

2) WIRE BREAKAGE SIMULATION AND WORKING CASES

According to the Chinese code 'Technical code for design overhead transmission line in medium-heavy icing areas'(Q/GDW 10182-2017) [22], the tension of wire breakage for suspended towers is considered to be 70% of the maximum use tension, while for ground wire breakage, it is 100% of the maximum use tension. Additionally, according to the Chinese code 'Code for design of 110∼750 kV overhead transmission line'(GB50545-2010) [24], the design safety coefficient for the conductors and ground wire at the suspension point should not be less than 2.25. Combined with the mechanical parameters in Table 1, the longitudinal, normal use force, and pull-off force of the conductor at different ice thicknesses are calculated.

The wire breakage case is calculated based on the following factors: wire breakage, −5°C temperature, ice, and no wind load. It is assumed that breakage occurred in the +X direction of the transmission tower, at the hanging point of span #1 near tower 1, and that the four- bundle conductor was broken singly. This study investigated the effect of longitudinal unbalanced tension generated by a broken wire on the bearing capacity of transmission tower 1. This study considers different foundation settlements of 0 m, 0.025 m, 0.05 m, and 0.075 m for both RT and JT. The location of the broken wire is shown in Fig. 1, and the working conditions of the broken wire are shown in Table 5.

B. ANALYSIS OF THE EFFECTS OF BOLT SLIPPAGE AND FOUNDATION SETTLEMENT ON THE BEARING CAPACITY OF TOWER-LINE SYSTEM UNDER INHOMOGENEOUS ICE-COVERING CONDITIONS

1) BEARING CAPACITY ANALYSIS OF TOWER-WIRE SYSTEM UNDER INHOMOGENEOUS ICE-COVERING CONDITIONS WITH FOUNDATION SETTLEMENT

Changes in the tower top displacement and bearing capacity of RT and JT under the action of inhomogeneous conductor ice cover are analyzed using the tower top displacement as an index. The tower-top displacements of the two models for

TABLE 5. Cases of wire breakage.

Case No.	Deformation category	Broken position
C0	No foundation settlement	Upper and middle conductors (at a and b) Upper and lower conductors (at a and c) Middle and lower conductors (at b and c)
C1	One foundation settlement	Upper and middle conductors (at a and b) Upper and lower conductors (at a and c) Middle and lower conductors (at b and c)
C2	Two foundations settlement	Upper and middle conductors (at a and b) Upper and lower conductors (at a and c) Middle and lower conductors (at b and c)
C3	Three foundations settlement	Upper and middle conductors (at a and b) Upper and lower conductors (at a and c) Middle and lower conductors (at b and c)

cases B0 and B1 are shown in Figure 11. The two models did not collapse within the range of 20 mm-60 mm of ice cover on the #2 span conductor. JT exhibits a significantly larger tower top displacement than does RT. The maximum tower top displacement reaches 2.45, 1.91, 1.72, and 1.73 times greater under the four settlements. This indicates that the bolt-slippage effect has a significant impact on the deformation of the transmission tower under inhomogeneous icing. Ignoring the bolt slip effect underestimates the displacement response of the tower under the action of inhomogeneous icing and overestimates the safety of the transmission tower.

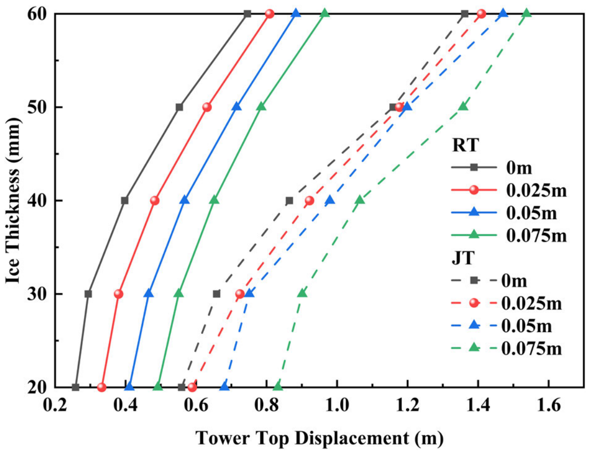


FIGURE 11. Tower top displacement without settlement under inhomogeneous ice cover.

Table 6 shows the number of failure members in the two models for three different foundation settlements and various working cases. Buckling failure did not occur for the case B0, but it did occur for the case B1-0.025 m. For the case B2, buckling failure occurred for all three settlement amounts, and for the case B3, it occurred with the settlement of 0.025 m. As bolt slippage generates additional internal forces at the tower legs [25], we selected some of the tower legs shown in Figure 12 as representative members for analysis. The members analyzed are member ZA, ZB, ZC, and ZD, which are the main members of the tower legs, and member AB, BC, CD, and DA, which are the diagonal members of the tower legs.

TABLE 6. Failure members of various cases inhomogeneous icing.

Case No.	Settlement(m)	Failure member	
		RT	JT
B0	0	/	/
B1	0.025	/	/
	0.05	DC, BC	DC
	0.075	DC	DC
B2	0.025	/	/
	0.05		
	0.075		
B3	0.025	/	/
	0.05	AB, AD	AB
	0.075	AB, AD	AB

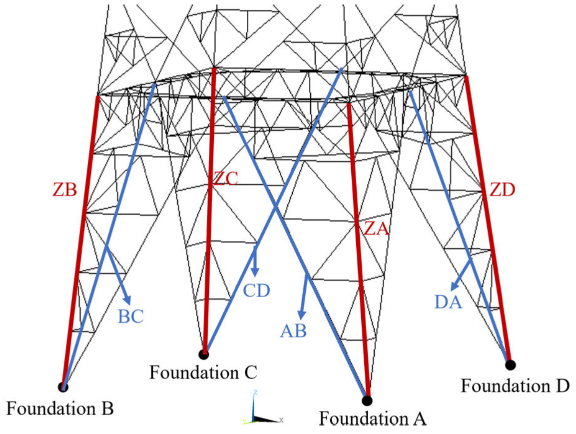
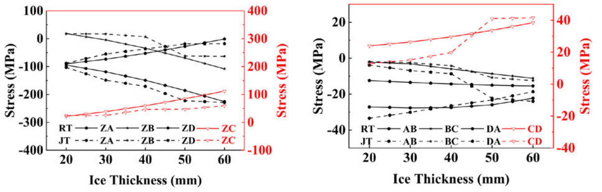
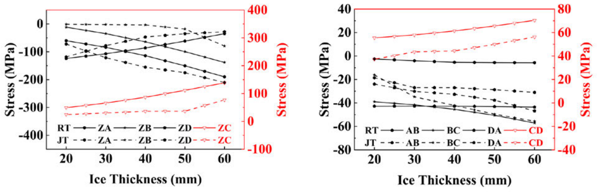


FIGURE 12. Representative members of tower legs under inhomogeneous icing conditions.



(a) Main members of case B0
(b) Diagonal members of case B0

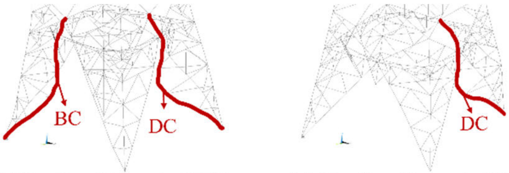


(c) Main members of case B1
(d) Diagonal members of case B1

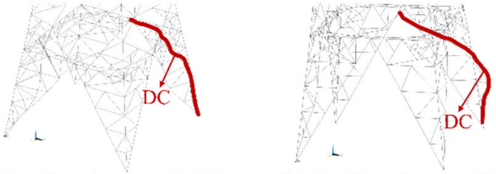
FIGURE 13. Relationship between stress of representative members and ice thickness under inhomogeneous ice coverage.

Figure 13 shows the stress variation plots for the cases B0 and B1-0.025 m. The stress in the bar increases with settlement, as shown in the figure. For the main material representative members, the stresses of the two models' representative members were similar when the ice cover was 20 mm. However, with an increase in ice thickness to 60 mm, there was a significant difference in the member stresses. The stresses of the representative members of RT changed more than those of JT, with maximum differences of 6.8 and 10.1 times, respectively. The members representing diagonal members, however, change from a 20 mm gap in ice cover to a 60 mm gap. In this case, the stress change in the representative member of JT is greater than that of RT, reaching maximums of 5.5 and 2.1 times, respectively. The text describes the impact of foundation settlement on bolt slippage for representative members of the main and diagonal members. Ignoring the effect of bolt slippage can lead to overestimation of the load carrying capacity of the main member and underestimation of the load carrying capacity of the diagonal members. Bolt slippage causes a slower decrease in the load carrying capacity of the main member and a more significant effect on the diagonal members of the tower leg.

The tower leg diagonal members of both models exhibited buckling as the foundation settlement increased. Figure 14 shows the buckling positions of the members for both models under settlements of 0.05 m and 0.075 m with 60 mm of ice cover in case B1. Evidently, the yielding members of the two towers differ. Specifically, the member BC and DC of RT with a settlement of 0.05 m yield, while only member DC of JT representative members yield at this time. This suggests that bolt slippage will impact the failure mode of the members.



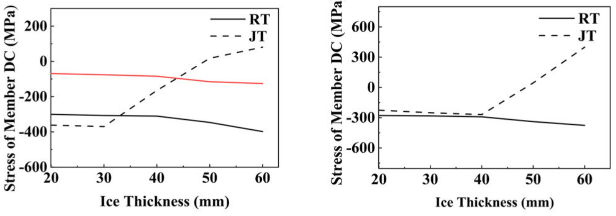
(a) RT with settlement of 0.05 m (b) JT with settlement of 0.05 m



(a) RT with settlement of 0.075 m (b) JT with settlement of 0.075 m

FIGURE 14. **Failure members of case B1 (Amplify deformation by 10 times).**

Figure 15 shows the stress variation of member DC with ice thickness for two settlement amounts of case B1. As shown in the figure, the destructive member stresses increase with foundation settlement. As the ice thickness increases, the destructive member stresses of RT remain relatively constant. However, the destructive member of JT begins to carry more force when covered with 30 mm and 40 mm of ice. Its stress then rapidly decreases and increases in the opposite direction due to the combined effect of the stress generated by the displacement of the tower top and the additional stress generated by the settlement of the foundation. It is evident that as the foundation settles and the thickness of the ice cover increases, the bolt-slippage effect causes the stress on the failure members to change more rapidly and significantly.



(a) Settlement of 0.05 m (b) Settlement of 0.075 m

FIGURE 15. **Relationship between stress of failure members and ice thickness of case B1.**

2) EFFECT OF BOLT SLIPPAGE AND FOUNDATION SETTLEMENT ON THE BEARING CAPACITY OF TOWER-LINE SYSTEM UNDER INHOMOGENEOUS ICE COVER CONDITIONS

Using the example of an ice cover thickness of 40 mm, under case B0 without foundation settlement, the tower top displacement of RT is 0.40 m. The tower top displacement of JT is 0.86 m, and the tower top displacement increases by 118% due to the bolt-slippage effect. Under the case B1 with a foundation settlement of 0.075 m, the displacement is yet to be determined. The tower top displacement of RT is 0.65 m, and the tower top displacement is displaced by 64% due to foundation settlement. This indicates that the bolt-slippage effect has the greatest influence on the deformation of the transmission tower when the conductor is inhomogeneously covered with ice. Ignoring the bolt-slippage effect will overestimate the safety performance of the transmission tower. It is important to consider this effect in any analysis of transmission tower safety.

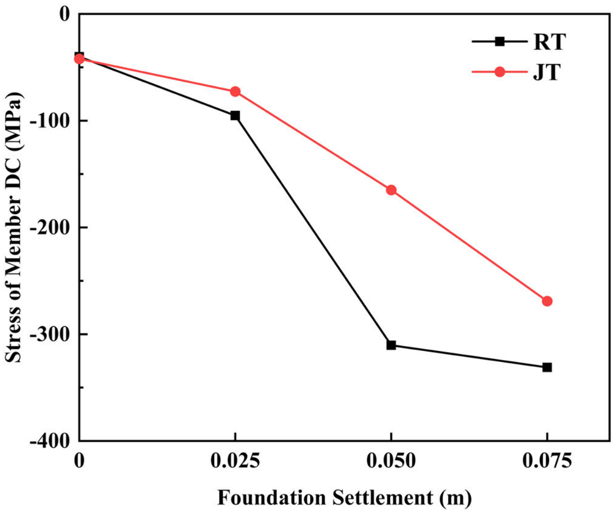


FIGURE 16. **Stress variation of member DC under 40mm ice.**

Figure 16 shows the stress change rule of the failure member DC with settlement of case B1 under 40 mm ice cover conditions. The figure indicates that the stress growth

TABLE 7. Ultimate ice thickness and failure members of various cases under broken wire cases.

Case No.	Settlement(m)	Broken position	Maximum ice thickness (mm)		Failure member	
			RT	JT	RT	JT
C0	0	① ab	36	33	/	/
		② ac	37	34		
		③ bc	38	35		
C1	0.025	① ab	36	35	BA	BA
		② ac	36	35	BA	BA
		③ bc	36	35	BA	BA
	0.05	① ab	37	33	BA	BA
		② ac	40	35	BA	BA
		③ bc	38	34	BA	BA
	0.075	① ab	38	35	BA	BA
		② ac	40	34	BA	BA
		③ bc	37	31	BA	BA
C2	0.025	① ab	40	38	/	/
		② ac	41	38		
		③ bc	42	39		
	0.05	① ab	37	33		
		② ac	37	35		
		③ bc	39	36		
	0.075	① ab	37	33		
		② ac	37	32		
		③ bc	36	32		
C3	0.025	① ab	40	38	AD, XC1, XC2	AD
		② ac	41	39	AD, XC1, XC2	AD
		③ bc	42	39	AD, XC1, XC2	AD
	0.05	① ab	37	32	AD, XC1, XC2	AD
		② ac	37	33	AD, XC1, XC2	AD
		③ bc	39	35	AD, XC1, XC2	AD
	0.075	① ab	31	30	CB, AD, XC2, XC3, HG	CB
		② ac	33	30	CB, AD, XC2, XC3, HG	CB
		③ bc	33	32	CB, AD, XC2, XC3, HG	CB

rate of the member in RT is faster and approaches the ultimate stress of the member as settlement increases. The bolt-slippage effect slows the decrease in the bearing capacity of the tower-line system when subjected to conductor inhomogeneous ice cover. Neglecting this effect leads to an underestimation of the settlement when the transmission tower is damaged, which affects the accurate assessment of the bearing capacity of the tower-line system.

C. ANALYSIS OF THE EFFECT OF BOLT SLIPPAGE AND FOUNDATION SETTLEMENT ON THE BEARING CAPACITY OF TOWER-LINE SYSTEM UNDER BROKEN WIRE CASES

1) BEARING CAPACITY ANALYSIS OF TOWER-LINE SYSTEM UNDER BROKEN WIRE CASES WITH FOUNDATION SETTLEMENT

To investigate the impact of bolt slippage and settlement on the bearing capacity of the tower-line system, we conducted a Pushover analysis under disconnection conditions for both RT and JT. We varied the settlement under case C0 and C3-① and used the tower top displacement as the limit index.

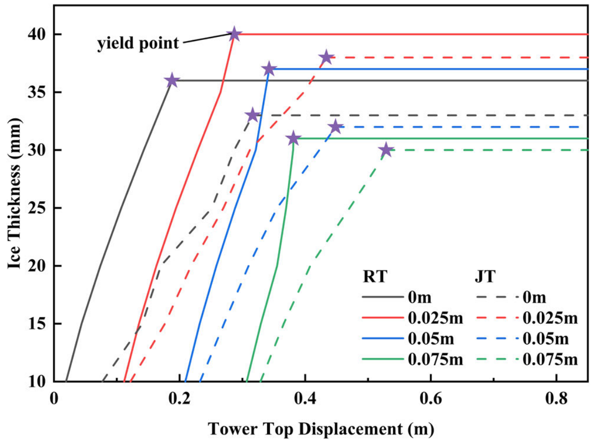


FIGURE 17. Tower top displacement of wire breakage.

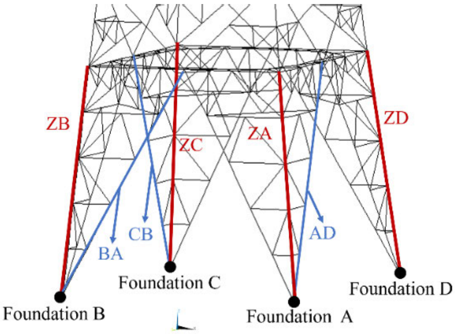
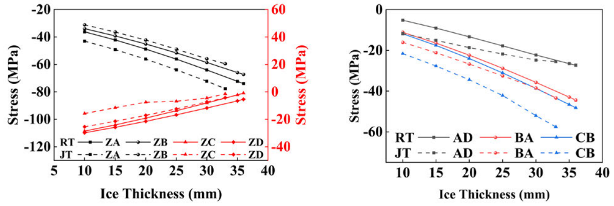


FIGURE 18. Representative members of tower leg of wire breakage.



(a) Main members (b) Diagonal members

FIGURE 19. Representative members of tower leg of wire breakage.

This allowed us to determine the corresponding conductor limiting ice thicknesses and analyze the stress changes of the representative members of the tower leg and the destroyed members under the limiting ice thicknesses. Figure 17 shows the displacement diagram of the tower top, while Table 7 displays the ultimate ice thickness and failure members for each working case.

Fig. 17 and Table 7 show that the tower top displacement of JT is significantly larger than that of RT and increases with increasing foundation settlement. Additionally, the ultimate ice thickness of RT model is greater than that of JT. Therefore, bolt slippage evidently affects the safety of the transmission tower under wire breakage and cannot be ignored. The tower top displacement in JT is significantly greater than that in RT under disconnected conditions. The maximums of the four settlements reach 3.21, 1.39, 1.32, and 1.39 times, respectively.

The impact of bolt slippage on the deformation of a transmission tower under wire breakage is significant. Neglecting this factor will result in an underestimation of the displacement response of the tower and an overestimation of its safety.

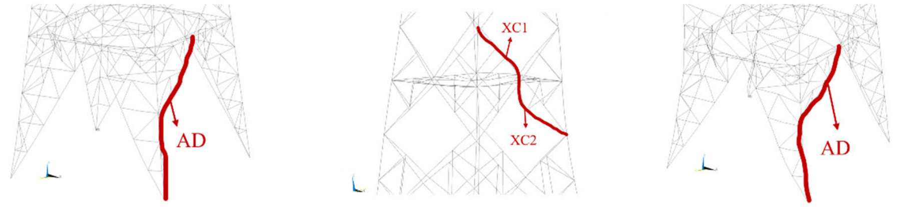
As the transmission tower did not experience any member buckling under the case C0 with an ice thickness under the limit, we use the main and diagonal members of the tower leg shown in Figure 18 to analyze the trend of member stress with changes in conductor ice-covering thickness when it is disconnected at position ab. The results are presented in Figure 19. As the ice cover thickness increases, the stress on the representative member of main member of RT changes more than that of JT, with a maximum increase of 1.03 times. Additionally, the stress on representative members of diagonal member of JT is greater than that of RT. It can be concluded that when the foundation is not settled, the bolt-slippage effect will cause a slower decrease in the bearing capacity of the main member of the tower leg but a more significant effect on the diagonal member. Neglecting the bolt-slippage effect leads to an overestimation of the change in the load carrying capacity of the main member of the tower-line system and an underestimation of the load carrying capacity of the diagonal member.

Under the limited wind speeds of the three settlements of case C3-① , when the two models reach their respective limiting ice thicknesses, some members exhibit buckling phenomena, and these members are damaged in this case. Figure 20 shows the damaged members corresponding to the three settlements of case C3-① (deformation magnified 10 times). As shown in the figure, for RT, during the settlement of foundation A, B, and D, not only the diagonal members of the tower legs are damaged, but also the diagonal members of the tower body and the members of the transverse diaphragm are damaged, As the settlement increases, the tower body diagonal damage moves downward. In contrast, JT only experiences damage to the tower leg and not the tower body. The damage locations for two towers models under the same settlement are not identical. The bolt-slippage effect affects the damage location of the members under these three cases and increases the load-bearing capacity of the tower-line system.

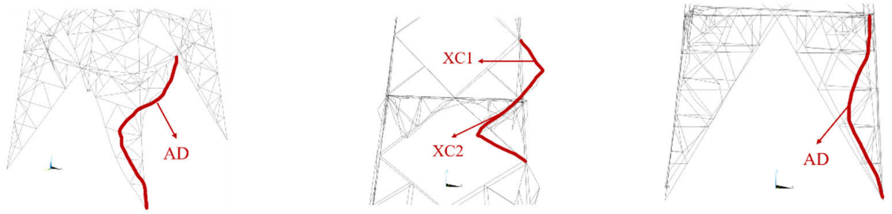
Since member HG failure does not affect the stability of the transmission tower in this paper, the stress of member HG is not discussed in case C3-① condition. Figure 21 illustrates the stress changes of the failure members AD and CB under three settlement amounts. The stress growth rate of the members in JT is greater than that in RT under the three settlement amounts. Additionally, the magnitude of the stress change is significantly larger than that of RT. As the thickness of the overlying ice increases, the stress on the two kinds of members in JT rapidly increases, approaching the ultimate stress of the members and making them more prone to failure. Ignoring the slippage action of bolts under the same settlement will result in an underestimation of the change in the bearing capacity of the tower-line system. Additionally, bolt slippage accelerates the decrease in the bearing capacity of the transmission tower. The destructive member stress also increases with settlement.

2) EFFECT OF BOLT SLIPPAGE AND FOUNDATION SETTLEMENT ON THE BEARING CAPACITY OF TOWER-LINE SYSTEM UNDER BROKEN WIRE CASES

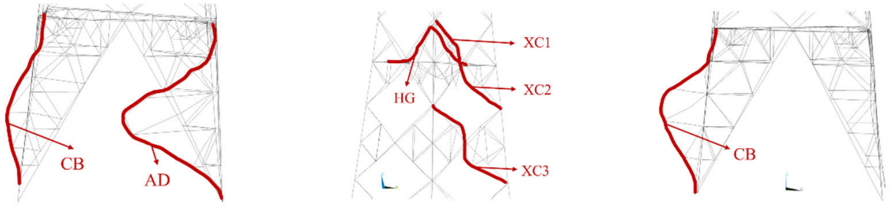
Figure 17 shows that for a conductor ice cover of 20 mm and no foundation settlement effect under the case C0, the tower top displacement of RT is 0.07 m, and the tower top displacement of JT is 0.17 m. The bolt-slippage effect increases the displacement of the top of the tower by 130%. In the case of C3-① of 0.25 m foundation settlement, the top of the model tower at RT is displaced by 0.16 m. Foundation settlement causes the tower top displacement to increase by



(a) RT tower legs-0.025 m (b) RT tower body-0.025 m (c) JT tower legs-0.025 m

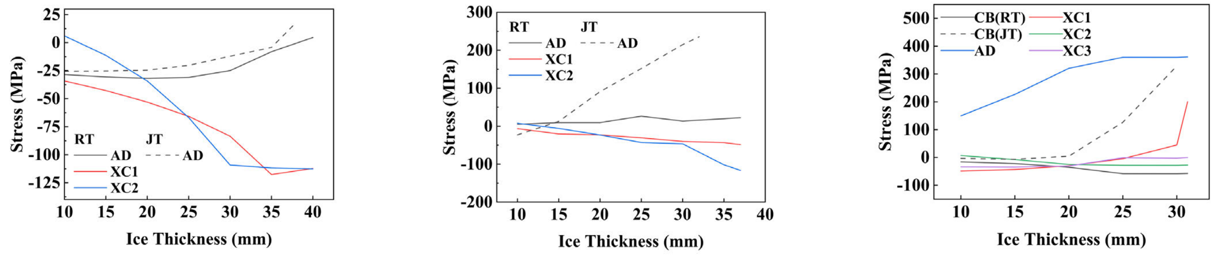


(d) RT tower legs-0.05 m (e) RT tower body-0.05 m (f) JT tower legs-0.05 m



(g) RT tower legs-0.075 m (h) RT tower body-0.075 m (i) JT tower legs-0.075 m

FIGURE 20. Failure members of case C3-① (Amplify deformation by 10 times).



(a) 0.025m (b) 0.05m (c) 0.075m

FIGURE 21. Stress of representative members during settlement of case C3-①.

120%. At a foundation settlement of 0.075 m, the tower top displacement of RT is 0.36 m. The foundation settlement increases the displacement of the top of the tower by 380%. The analysis shows that bolt slippage is the main factor in the deformation of a transmission tower when subjected to a broken wire. As the foundation settlement increases, it has a greater impact on the tower top displacement. Ignoring the bolt-slippage effect would lead to an overestimation of the safety performance of the transmission tower.

Figure 22 presents the stress change rule for the damage member BA under case C1-① , using both RT and JT, with respect to the amount of settlement. The figure shows that the stress change amplitude is larger and the growth rate is faster for RT. At a settlement of 0.075 m, the stress in RT member reached 1.66 times that of JT, approaching the limit stress

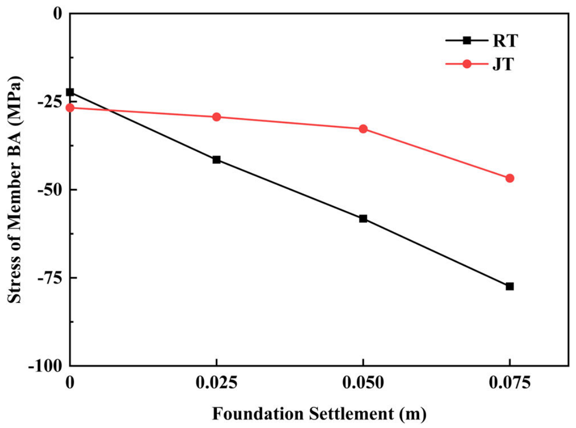


FIGURE 22. Stress variation of member BA under 20mm ice of case C1-①.

of the member. The bolt-slippage effect slows the decrease in the bearing capacity of the tower-line system under wire breakage cases. Ignoring this effect leads to underestimation of the settlement amount when damage occurs, which affects the accurate assessment of the bearing capacity of the tower-line system.

V. CONCLUSION

In this paper, the bearing capacities of an ideal rigid frame model of a transmission tower (RT) and a transmission tower model considering the bolt-slippage effect (JT) under static wind loading and unbalanced longitudinal stress are analyzed via finite element simulation in the case of foundation settlement. The main conclusions are as follows:

(1) The bolt-slippage effect will significantly increase the deformation and displacement response of the transmission tower, resulting in overestimation of the limit state of the structure, thus affecting the safety of the transmission tower.

(2) The failure members of the two tower-line system models with foundation settlement under the two kind of loads are mainly distributed at the tower legs, and the stress distribution of the members is affected by the bolt-slippage effect. The failure position and failure mode of the members of the two models are not exactly the same.

(3) The stress growth rate of the failure member of JT is greater than that of RT. Ignoring the bolt-slippage effect will overestimate the bearing capacity of the transmission tower-line system.

(4) With the increase of settlement, the failure bar of RT will reach the ultimate stress faster and enter the limit state. The members of JT enter the limit state more slowly and the ultimate settlement is larger. The bolt slippage makes the bearing capacity of the tower-line system decrease more slowly.

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