Research and engineering verification of high-voltage cable laying method under complicated working conditions

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Abstract. In the light of the characteristics of the cable construction model under complicated working conditions, it is found that there is no engineering experience to calculate the traction force of the stay tube section and the arc high drop section. This paper establishes the corresponding engineering mechanics models according to the construction site environment, which determines the engineering calculation formulas by theoretical deduction and the on-site industrial test verification, thus realizing the safe, economical and efficient laying of high-voltage cables under complex working conditions. Finally, the 220kV East Traction Station project is taken as an example to verify the proposed construction scheme. The results show that the laying and bending tasks can be successfully completed and all the indicators are in perfect conformity with the technical specifications.

1. Introduction
Cable line is known as the "blood vessel" of urban power grid. In recent years, it is showing a rapid development trend [1]. The rapid growth of three-dimensional traffic construction of urban inner ring elevated highway, high-speed rail and light rail has led to the emergence of stay tube section and high drop section high-voltage cable laying projects [2, 3]. This kind of high-voltage cables is mainly the power supply line of substation or high-speed railway and other important users, with complex construction environment and extremely demanding of the reliability of power supply. In the past, due to the lack of effective laying means of stay tube section and high drop section high-voltage cables, the operation efficiency is insufficient, and no effective solution has been found at home and abroad [4, 5]. The complete set of construction technology and matching equipment are still in a blank all over the world [6].

This paper establishes the engineering mechanics models and the calculation methods of traction force of the stay tube section and the high drop section according to the complex construction site environment. It satisfies the technical requirements of the design code and the eighteen countermeasures of the SGCC, which stipulates that the cable connectors should not be arranged on the bridge frame, and provides important technical reference for the construction of high-voltage cables.

2. Establishment of simplified model for laying large cross-section and high drop-section cables
In order to facilitate the research, there will set up a model based on the 220kV East Traction Station project in the following.
2.1. Characteristic description of East Traction Station project
The cable line of 220kV Changjiang to Wuxi East Traction Station consists of two circuits, one is from 220kV GIS to the side of Traction Station, the other is from 220kV GIS to Xiangnan, each of which has a length of 10km. The whole channel includes cable interlayer, cable trench, row tubet, power well, stay tube section, high-drop section and so on. There are 6 outdoor terminals, 6 GIS terminals and 192 intermediate joints in total. The project has 9 high drop sections, and the construction condition is extremely complex.

2.2. Typical model for continuous laying of high-voltage cable with stay tube section and high drop section
Based on the above analysis, a typical integrated project model can be obtained from reference to some regions according to the survey data. On the basis of the analysis of the model, the principle of the continuous laying process and the related simplified calculation method will be determined, so as to guide the practical application of such projects. The specific model is shown in Figure 1 below:

![Figure 1. Typical high-voltage cable laying models under complicated working conditions.](image)

The main characteristics of the model are as follows:
A. The range of values for L2 is generally between 20 and 30m, and the section of the model usually has a drop of more than 30m, which needs to meet the continuous laying condition of single channel.
B. The range of values for L1 is generally between 20 and 200m, and the model generally has a long stay tube length and a narrow connected well.

Considering that the difficulty of the project lies in stay tube section (L1) and high drop section (L2), the following article will focus on these two sections.

3. Research on simplified calculation formulas of traction for stay tube section
At present, there is no formula for the traction force of arbitrary stay tube laying path in the existing manual of "Calculation Formula of Traction Force of Cable Line Parts" [7, 8, 9]. In view of the above-mentioned facts, this article launches the research aiming at simplified calculation formulas of traction for stay tube section in the first place.

A typical layout diagram for stay tube section is shown in Figure 2. According to the laying trajectory of the high-voltage cables, the axial tension can be divided into three sections: the incident section, the
transition section and the horizontal section. Finally, we can get the maximum traction required. Detailed calculation steps are given below.

Figure 2. Laying trajectory of the high-voltage cables.

The laying trajectory of Figure 2 can be further simplified, resulting in a structural model as shown in Figure 3 below, in which the high-voltage cable is pulled from the left side into the right side.

Figure 3. Idealized model of the incident section.

In the figure above, $L$ is the horizontal distance of the cable laying; $\theta_1$ is the incident angle of the cable laying; $\theta_2$ is the exit angle of the cable laying; $h_1$ is the depth of the incident end of the cable laying; $h_2$ is the depth of the exit end of the cable laying; $R_1$ and $R_2$ represent the radius corresponding to the arc. In addition, $W$ is set to the weight of unit length of the cable and $\mu$ is set to the coefficient of friction.

According to the force analysis, the axial traction force required for each segment of cable can be solved separately as shown below:

Force in straight AB segment:

$$F_{\text{AB}} = 9.8(h_1 - R_1(1 - \sin(\frac{\pi}{2} - \theta_1))) \cdot \csc \theta_1 \cdot (\mu \cos \theta_1 - \sin \theta_1)$$  \hspace{1cm} (1)

Force in straight EF segment:

$$F_{\text{EF}} = 9.8W(h_2 - R_2(1 - \sin(\frac{\pi}{2} - \theta_2))) \cdot \csc \theta_2 \cdot (\mu \cos \theta_2 + \sin \theta_2)$$  \hspace{1cm} (2)

Force in arc BC segment:
\[ F_{\text{BC}} = 9.8 \mu W R_1 \cos\left(\frac{\pi}{2} - \theta_1\right) - 9.8 W R_1 + 9.8 W \sqrt{R_1^2 - \left(R_1 \cos\left(\frac{\pi}{2} - \theta_1\right)\right)^2} \]  (3)

Force in arc DE segment:

\[ F_{\text{DE}} = 9.8 \mu W R_2 \cos\left(\frac{\pi}{2} - \theta_2\right) + 9.8 W R_2 - 9.8 W \sqrt{R_2^2 - \left(R_2 \cos\left(\frac{\pi}{2} - \theta_2\right)\right)^2} \]  (4)

Force in horizontal CD segment:

\[
F_{\text{CD}} = 9.8 \mu W (L - R_1 \cos\left(\frac{\pi}{2} - \theta_1\right) - R_2 \cos\left(\frac{\pi}{2} - \theta_2\right)) \\
- (h_1 - R_1 (1 - \sin\left(\frac{\pi}{2} - \theta_1\right))) / \tan \theta_1 \\
- (h_2 - R_2 (1 - \sin\left(\frac{\pi}{2} - \theta_2\right))) / \tan \theta_2 
\]  (5)

According to the above formulas (1) to (5), the comprehensive tensile force can be obtained:

\[ T = F_{\text{AB}} + F_{\text{EF}} + F_{\text{DE}} + F_{\text{CD}} \]  (6)

In summary, the comprehensive tensile force of all the stay tube section laying in complex conditions can be calculated according to the formulas derived above. Specifically, the maximum traction force required for laying high-voltage cables in different lengths and different types of stay tubes can also be calculated, with reference to the laying trajectory model given in the actual laying scheme.

4. Study on simplified calculation formula of traction force for high drop section

Consistent with what has mentioned previously, a simplified diagram of the relevant model will be given at first. In order to obtain a simplified model of the arc-shaped vertical laying under high-drop section, the High Drop Section portion in Fig. 1 is simplified to the model in Fig. 4 below.

![Figure 4. Idealized arc-shaped traction model.](image)

According to the force analysis, the required traction force can be obtained for each segment:

Force in arc DC segment:
\[ T_c = \frac{9.8WR}{1 + \mu^2} \left[ 2\mu \sin \theta - (1 - \mu^2)(e^{\mu\theta} - \cos \theta) \right] + T_\mu e^{\mu\theta} \] (7)

Force in CB segment:
\[ T_b = T_c + 9.8\sqrt{2WL_e} \left( \mu \cos \frac{\pi}{4} - \sin \frac{\pi}{4} \right) \] (8)

Force in arc BA segment:
\[ T_A = T_b e^{\mu\theta} - \frac{9.8WR}{1 + \mu^2} \left( (1 - \mu^2) \sin \theta + 2\mu(e^{\mu\theta} - \cos \theta) \right) \] (9)

The maximum allowable traction of the cable will be further considered:
\[ T_m = \sigma A \] (10)

In the above formula, \( \sigma \) is the allowable traction strength of the conductor (N/mm\(^2\)) and \( A \) is the cable conductor cross-sectional area (mm\(^2\)).

Thus, it is possible to deduce the longest draw tube length allowed for cables of different cross-sectional areas under various track type conditions. In addition, in order to ensure that the cable tension does not exceed the limit value, a safety factor can be set [10].

For most cases, the caisson height of the three layers is about 15-30m, and the value range of \( R \) is 5-10m. By setting the coefficient ratio between the theoretical formula and the simplified formula in engineering practice, the ratio of the safety factor is 1.56, and the practical simplified formula can be obtained.

5. Engineering verification

5.1. Ways to reduce traction
According to the design code, the traction force of 220kV large cross-section cable should not exceed 70*2500=175000N/mm\(^2\). Through the simplified formula proposed in this paper, the traction force of cable laying in the stay tube section and the high drop section can be calculated, and the traction force can be reduced to meet the design specifications by the following ways:

A. Reducing the various resistance in the traction process is an effective way to limit and reduce the traction force. For example, the friction resistance can be reduced by arranging pulleys reasonably, and the friction can be reduced by applying lubricants in places where contact friction is easy, such as between pipe walls and cables, between cable shafts and supports.

B. The traction speed of the hoist should be in accordance with the speed of the cable conveyor when a good linkage control device is installed. Whether the speed is synchronous or not is the key to ensure the quality of cable laying, even if the slight difference between the two will be directly reflected through the conveyor to the cable outer protective layer.

C. If conditions permit, in order to significantly reduce the risk of cable laying damage, it is necessary to increase the proportion of conveyor output and reduce the proportion of tractor output during the cable laying process.

5.2. Engineering case introduction
Taking the 220kV East Traction Station project as an example, the optimization design is carried out according to the traction calculation model proposed in this paper. The concrete results are as follows:

A. Determination of bending radius.
The bending radius should not be less than 3m, and this project is basically controlled at 3.5m.

B. Determination of the sequence of high drop continuous laying project.

The laying sequence is generally as follows: Power Cable Trench, Row Tube, Power Well, Slope Culvert Section, Bridge Frame, Tunnel (from left to right).

C. Selection of traction method for high drop continuous laying project.

Considering that the stay tube is generally over 66m, the project uses synchronous traction control. A total of eight conveyors were used in the laying project, with at least five rollers at each turn to ensure traction requirements.

The scene construction location situation of the project will be given in Figure 5:

![Figure 5. Scene construction location situation of the project.](image)

According to the above technical scheme, the laying and bending work of the high-voltage cables has been successfully completed. After inspection, the laying and bending operations have not caused damage to the cable, and all the indexes are in good agreement with the requirements of technical specifications, which provides a valuable reference scheme for the construction of high-voltage cables in this field.

6. Conclusion

In this paper, a safe, effective and convenient engineering calculation formula of traction force for stay tube and high drop section of high-voltage cables laying projects is established for the first time. The safe and economical laying method of high-voltage cable lines under complex working conditions is realized, which fully meets the technical requirements of relevant design criteria.

The scheme has been successfully applied in the project of 220kV East Traction Station. The results show that the proposed scheme fully meets the requirements of technical specifications which can significantly improve the construction efficiency and provide a valuable technical scheme for cable laying method.

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