Application of double-enlarged excavation foundation in transmission line engineering

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Abstract. This paper introduces the application of double-enlarged excavation foundation in transmission line engineering. Based on the comparison of expanding excavation foundation and double-enlarged excavation foundation, this paper expounds the advantages of double cut and enlarge base, such as high bearing capacity, convenient construction, low cost, safety and environmental protection. It introduces the application of the double-enlarged excavation foundation in the transmission line project through an engineering example, and expounds that the type of foundation is suitable for the corner tower with large foundation force in the transmission line in the hilly area, which has good economic and social benefits.

1. Introduction
The common foundation types in hilly area and low mountainous area are straight column plate flexible foundation and digging and enlarged pile foundation [1]-[2]. The straight column plate flexible foundation belongs to the form of large excavation foundation. The use of this foundation in hilly and low mountain area will cause large foundation excavation and damage the surrounding environment. However, the excavated foundation has the advantages of small occupation of construction site, low noise and low cost. It is widely used in foundation engineering in hilly area to make full use of the bearing capacity of undisturbed soil and replace the formwork with soil [3]-[4].

However, due to the large structural load of the corner tower, the pile foundation with large bearing capacity is required to bear large downward pressure and uplift force. The measures of lengthening the pile length or increasing the bottom width are often adopted to solve the problem for enlarged pile foundation, which brings inconvenience to the construction personnel.

Therefore, a kind of double-enlarged excavation foundation emerges as the times require. The bearing mechanism of the foundation is scientific and reasonable. It not only reduces the force at the pile end, but also expands the bearing area. It gives full play to the role of side resistance and end resistance, and achieves the purpose of improving the bearing capacity.

2. Engineering overview and geological conditions
Shangyi-Zhangbei 500kV Line project is located in Shangyi County and Zhangbei County of Zhangjiakou. The second section of the line from the north of Xi Shuiquan village to the north of Da Xiwan village is a low mountainous area with undulating terrain. The lithology of strata along the line is gravel and basalt, as shown in figure 1.
Figure 1. Exposed basalt landform

The second section of the project is covered with crushed stone layer and completely weathered or strongly weathered rock mass, which has good bearing performance and good self-reliance, which is convenient for excavation and has favorable conditions for adopting excavation foundation.

3. Comparison and selection of foundation schemes

3.1. Common foundation types in hilly area

The common foundation types in hilly area are straight column plate flexible foundation and enlarged pile foundation, as shown in figure 2 and figure 3.

Figure 2. Straight column plate flexible foundation

Figure 3. Enlarged pile foundation

The buried depth of the straight column plate flexible foundation is generally 4.0m-5.0m, the land acquisition area and excavation volume are large, so it is difficult to excavate, easy to collapse and take a long time.

Because the excavation foundation mainly relies on manual excavation to form holes, in order to ensure the safety of construction personnel and take into account the economy, the commonly used excavation foundation size is generally small\(^5\). However, for the corner tower with large partial load of 500kV transmission line, if the conventional enlarged foundation is still used, the column diameter and base plate size will be greatly increased. This is bound to increase the risk of construction.

Therefore, it is very necessary to take effective measures to improve the excavated foundation so that the foundation can not only meet the requirements of large bearing capacity, but also save the material consumption to the maximum extent. Therefore, in the hilly area of the line project in this section, when the corner tower with large foundation force is recommended, a new foundation type
which is called double-enlarged excavation foundation is recommended.

### 3.2. Introduction of double-enlarged excavation foundation

The double expanding head excavation foundation is composed of pile body and two plates, which jointly bear the tower load, as shown in figure 4. A plain concrete plate is added in the middle of the excavated belled pile to become the double-enlarged excavation foundation. The foundation type has the characteristics of high bearing capacity and low pressure shrinkage. Due to the full play of the pile side friction resistance, plate end resistance and pile end resistance, the uplift and downward bearing capacity of the foundation are greatly improved. The construction is general, while the excavation volume and the damage to the environment is small.

![Figure 4. Sketch of jumper wire](image)

In theory, due to the increase of the number of expansion head, the occluding surface between the expanded head and the surrounding undisturbed soil is also increased. When the foundation is subjected to vertical loads such as uplift or downward pressure, the soil around the enlarged head can provide more shear planes to bear a larger proportion of vertical load. At the same time, the bearing capacity of the undisturbed foundation soil at the bottom of each expansion head can be well utilized, as shown in figure 5.

![Figure 5. Cut the shear surface of the foundation](image)

In the mechanism of pile forming, the double-enlarged excavation foundation uses the better soil
layer in the middle and lower part to transfer the load to the soil layer through the concrete plate, which not only reduces the pile end force, but also expands the bearing area, so as to improve the bearing capacity. In terms of load transfer, each concrete plate is stressed, but the upper concrete plate first bears most of the load. With the gradual increase of pile top load, the stress of middle and lower plate also increases, so that the bearing capacity of single pile is gradually improved. Due to layered bearing, under the action of working load, the proportion of pile end force decreases, thus ensuring the stability of pile end soil.

The description of the actual failure surface is the basis for establishing the calculation formula. For the double-enlarged excavation foundation with $h \leq 5d$ ($h$ is the plate spacing and $d$ is the pile diameter), the failure surface is shown in figure 6(a). For the double-enlarged excavation foundation with $h > 5d$, the failure surface is shown in figure 6(b), and the uplift bearing capacity and compressive bearing capacity are analyzed according to the model of cast-in-place pile[6-8].

![Figure 6: Failure mode of double-enlarged excavation foundation](image)

3.3. Study on foundation of double-enlarged excavation foundation

The design of double-enlarged excavation foundation includes the following contents: uplift bearing capacity, down pressure bearing capacity, horizontal bearing capacity, displacement calculation and single pile body calculation, etc. The structure shall meet the requirements of Technical code for building pile foundation (JGJ94-2018), Technical specification for design of overhead transmission line foundation (DL/T 5219-2016), Interim technical specification for branch plate grouting of thermal power plant (DLGJ153-2000).

The calculation formulas of uplift bearing and downward bearing capacity listed in this chapter are applicable to all kinds of soil conditions[9-12]. It is only necessary to check the corresponding soil parameters in relevant specifications and geological reports.

3.3.1. Calculation of bearing capacity under compression about double-enlarged excavation foundation

The bearing capacity of double-enlarged excavation foundation is calculated according to the following formula[13-15]:

$$Q_{uk} = Q_{sk} + Q_{pk} = u \sum \psi_i q_{si} l_i + \sum \psi_i q_{pk} A_p + \psi_i q_{pk} A_p$$  

In the formula:

- $Q_{uk}$—Standard value of vertical ultimate bearing capacity of single pile (kN);
- $Q_{sk}$—Standard value of total ultimate lateral resistance of single pile (kN);
$Q_{pk}$—Standard value of total ultimate end resistance of single pile (kN);
$u$—Perimeter of main diameter pile (m);
$q_{sik}$—Standard value of ultimate lateral resistance of the $i$ layer soil on pile side. If there is no accurate value, the value can be taken according to table 5.3.5-1 of JGJ94-2018, (kPa);
$l_i$—The height of packing should be subtracted from the thickness of the $i$ layer of soil, (m);
$q_{pk}$—Standard value of ultimate end resistance of soil at the bottom of main pile. If there is no accurate value, it can be taken according to table 5.3.5-2 of JGJ94-2018, (kPa);
$Ap_i$—The horizontal projection area of the plate deducting the section area of the main pile ($m^2$);
$Ap$—Section area of main pile tip ($m^2$);
$s_i\varphi$—Size effect coefficient of lateral resistance of diameter pile, it can be taken as per table 1;
$p\varphi$—Size effect coefficient of end resistance of diameter pile, it can be taken as per table 1.

Table 1. Side resistance and end resistance dimension effect coefficient of diameter cast-in-place pile

| Soil category         | Clay and silt | Sand and gravel soil |
|-----------------------|---------------|----------------------|
| $\psi_{si}$           | 1             | $(0.8 / d)^{1/3}$    |
| $\psi_p$              | $(0.8 / D)^{1/4}$ | $(0.8 / D)^{1/3}$ |

Note: $D$ in the table is the diameter of pile.

The design value of bearing capacity is shown as follows:

$$R = Q_{sa} / \gamma_s + Q_{pk} / \gamma_p$$

(2)

When the standard value of the bearing capacity of single pile is determined according to the static load test, the design value of vertical bearing capacity of foundation pile is shown as follows:

$$R = Q_{sa} / \gamma_{sp}$$

(3)

In the formula:

$\gamma_s$—Partial coefficient of pile side impedance force, it can be taken as table 2;

$\gamma_p$—Partial coefficient of pile tip impedance, it can be taken as table 2;

$\gamma_{sp}$—Partial coefficient of pile lateral resistance and end resistance, it can be taken as table 2.

Table 2. Resistance coefficient of vertical bearing capacity about cast-in-place pile

| Tower type                                | $\gamma_s = \gamma_p = \gamma_{sp}$ |
|-------------------------------------------|--------------------------------------|
| Static load test method                   | Empirical parameter method           |
| Tangent tower                             | 1.10                                 | 1.10 |
| Tension tower (0° angle) and straight angle tower | 1.30                                 | 1.30 |
| Corner tower, terminal tower and large span tower | 1.60                                 | 1.60 |

3.3.2. Calculation of uplift capacity about double-enlarged excavation foundation

The uplift ultimate bearing capacity is calculated according to the following formula

$$R = U_k / \gamma_s + G_p = \sum \lambda q_{sa} u l / \gamma_s + G_p$$

(4)

In the formula:

$U_k$—Standard value of ultimate uplift bearing capacity of single pile (kN);

$G_p$—Design value of single pile weight, for plate pile, the design value of pile weight shall be calculated by determining the circumference of pile body according to table 3, (KN);
$u_i$—The perimeter of the damaged surface of the plate pile is taken as table 3, (m);
$q_{u,i}$—Ultimate compressive resistance of the $i$ layer of soil on pile side surface;
$\lambda_i$—Uplift coefficient, it can be taken as per table 4.

### Table 3. Surface Perimeter of Disk Pile Failure

| Length from one plate bottom to next plate bottom $l_i$ | $\leq 5d$ | $> 5d$ |
|------------------------------------------------------|----------|--------|
| $u_i$                                                 | $\pi D$  | $\pi d$ |

### Table 4. Uplift coefficient $\lambda_i$

| Soil                  | Uplift coefficient $\lambda_i$ |
|-----------------------|---------------------------------|
| Sandy soil            | 0.50~0.70                      |
| Clay and silt         | 0.70~0.80                      |

Note: When the ratio of pile length $l$ to pile diameter $d$ is less than 20, take the smaller value of $\lambda_i$.

3.3.3. Calculation of horizontal bearing capacity and displacement about double-enlarged excavation foundation

The calculation of horizontal bearing capacity and displacement about double-enlarged excavation foundation can be carried out according to ordinary cast-in-place pile. For specific calculation method, it can refer to section 11.6 of Technical specification for foundation design of overhead transmission line (DL/T 5219-2016).

3.3.4. Ontology computing about double-enlarged excavation foundation

The Ontology computing of double-enlarged excavation foundation can be carried out according to ordinary cast-in-place pile. For specific calculation method, it can refer to section 11.6 of Technical specification for foundation design of overhead transmission.

3.4. Technical and economic demonstration of double-enlarged excavation foundation

The foundation force of the tangent tower in the transmission line is small. If the double-enlarged excavation foundation is used, the calculated pile diameter is generally less than 1m. If the pile diameter is too small, it will bring a lot of invariance to the construction. After increasing the pile diameter, the buried depth of the foundation will often be reduced to 5 times of the pile diameter or slightly larger than 5 times of the pile diameter, so it is meaningless to add a plate in the middle.

In hilly areas, if the conventional excavation foundation is adopted for the corner tower of transmission line, the construction risk will be increased. Therefore, the advantages of double-enlarged excavation foundation are highlighted. The double-enlarged excavation foundation has the advantages of good mechanical performance, high bearing capacity, simple construction technology and little impact on the environment. It is completely feasible to apply the corner tower with large force in the transmission line in hilly area. However, whether it can be widely used in the engineering still needs to compare the economy of double-enlarged excavation foundation.

Most of the corner towers in this section are 5C3-SJC1 and 5C3-SJC2. The corner tower with large foundation force is selected. Taking 5C3-SJC2 tower as an example, the research and economic comparison are carried out\[16\]. For 5C3-SJC2 corner tower, foundation force is listed in table 5 below.

### Table 5. Load of tower foundation about 5C3-SJC2

| Type                | Downforce load (kN) | Uplift load (kN) |
|---------------------|---------------------|------------------|
|                     | $N$ | $Nx$ | $Ny$ | $T$ | $Nx$ | $Ny$ |
| 5C3-SJC2 corner tower | 3161.38 | 587.36 | 469.95 | 2590.25 | 490.87 | 415.46 |
According to the geological conditions, the groundwater level is 20m, gravel soil weight $\gamma = 20\text{kN/m}^3$, cohesive force $c = 30\text{kPa}$, internal friction angle $\phi = 30^\circ$, characteristic value of bearing capacity $f_{ak} = 150\text{kPa}$, $q_{sk} = 150\text{kPa}$, $q_{pk} = 800\text{kPa}$. After the multi scheme optimization design of double-enlarged excavation foundation and enlarged pile foundation, the material consumption of the optimal scheme of each foundation type is listed in table 6.

Table 6. Economic comparison of corner tower foundation about 5C3-SJC2

| Index                  | Concrete | Amount of reinforcement | Earthwork volume | Comprehensive cost |
|------------------------|----------|-------------------------|------------------|--------------------|
|                        | m$^3$    | kg                      | m$^3$            | Milion             |
|                        | Relative value | Relative value | Relative value | Relative value |
| Double-enlarged         | 79.30    | 7406                    | 86.0             | 0.2468             |
| foundation              | 88.3%    | 94.2%                   | 86.7%            | 92%                |
| Enlarged pile foundation | 89.83    | 7860                    | 99.3             | 0.2680             |
|                        | 100%     | 100%                    | 100%             | 100%               |

The comparison of concrete consumption, reinforcement consumption, earthwork volume and comprehensive cost of the two schemes of double-enlarged excavation foundation and enlarged pile foundation are shown in figure 7.

Figure 7. Comparison of double-enlarged excavation foundation and enlarged foundation

It can be seen from the figure 7 that the concrete consumption, reinforcement amount, earthwork volume and comprehensive cost of the double-enlarged excavation foundation are relatively lower, which are about 88.3%, 94.2%, 86.7% and 92% of the enlarged pile foundation respectively. Therefore, the double-enlarged excavation foundation has obvious advantages, which also has little damage to the ecological environment.

To sum up, it is feasible to use the double-enlarged excavation foundation in the corner tower of transmission line project in hilly area. This foundation has good economic and social benefits.
4. Construction and acceptance of double-enlarged excavation foundation

The construction and acceptance of double-enlarged excavation foundation is the same as that of enlarged pile foundation. It refers to section 6.6 of Technical code for building pile foundation (JGJ 94-2008). The construction situation is shown in figure 8.

![Construction of double-enlarged excavation foundation](image)

Figure 8. Construction of double-enlarged excavation foundation

5. Conclusions and recommendations

The bearing mechanism of double-enlarged excavation foundation is scientific and reasonable. It not only reduces the pile end force, but also expands the bearing area, fully plays the role of side resistance and end resistance, achieves the purpose of improving the bearing capacity, and has great bearing potential. In the corner tower of transmission line in hilly area, the advantage of using double-enlarged excavation foundation is highlighted. Compared with the conventional enlarged pile foundation, the concrete consumption, reinforcement amount, earthwork volume and comprehensive cost are lower, which has better economic and social benefits.

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