Frost-Heave Deformation and Prevention Technology of Power Transmission and Transformation Foundation under Extreme Boundary Temperature

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Abstract. Freezing and thawing disasters in seasonal frozen soil areas seriously affect the safety of power transmission and transformation projects. Studying the distribution of soil temperature and deformation under thermal insulation foundations is an important basis for the analysis of foundation stability in seasonal frozen soil areas. The thermal protection structure is closely related to the thickness of the insulation layer and the external thermal field. This dissertation takes the typical tower foundation of the 750 kV Hexi Power Grid Project and the geological conditions of the Shule River area in Gansu as the research objects. The theoretical analysis and numerical simulation methods are used to consider the impact of different thermal protection structures on the tower foundation and surrounding soil under extreme boundary temperatures. The influence of body deformation, stress, and temperature changes was analyzed. Through comparative analysis, it is found that the optimized structural form can effectively increase the temperature of the soil in extreme environments, avoid frost heave, and meet the design requirements for bearing capacity. In addition, the thermal-mechanical coupling analysis of the foundations of the initial temperature fields of different boundaries is carried out, and the applicability of the insulation foundation under different boundary conditions is discussed.

1. Introduction

The power transmission and transformation project in Hexi area inevitably has to pass through a large area of seasonal frozen ground. In the seasonal frozen ground area, due to the poor thermal stability of frozen soil, strong hydrothermal activity, and extremely sensitive to environmental changes, the transmission and transformation will be affected. The design, construction and safe operation of electrical engineering foundation pose a serious threat. On the contrary, under the influence of rising ground temperature or artificial activities, frozen soil will also sink due to melting. The main hazard is uneven settlement or overturning of the tower foundation.

In fact, the problem of soil frost heave deformation is a multi-physics coupling problem. Harlan [1] proposed a coupled mathematical model of water-heat transfer during soil freezing. Konrad [2] established a semi-empirical model takes into account the empirical equation of frost, frost heave amount provides a solution approach for calculation. Gilpin [3] regards ice as an undeformable rigid body with a linearly stable temperature field inside. Based on the nonlinear Burgers equation, Miao
Tiande et al. [4] established a water-heat coupling model with phase change in solid and liquid two-phase media. Li Ning, Chen Feixiong et al. [5] established the equilibrium equations of porous multiphase micro-element bodies in frozen soils, the mass conservation equations and energy conservation equations of porous solid-liquid media, and further analyzed the frost heave and thaw sedimentation phenomena of frozen soils. Lei [6] to elastoplastic deformation and heat transfer theory, deduced frozen soil subgrade Temperature - stress - distortion dimensional theoretical model.

Li Dong et al. [7] optimized the laying length of foam concrete insulation boards on both sides of the subgrade by numerically simulating the temperature field of the subgrade under different subgrade settings based on the on-site monitoring data of the Hazi passenger special section. Xu Jian et al. [8] found through the simulation of the frost heave calculation model that the laying of insulation boards on the frozen soil subgrade has a significant effect on the elevation of the freezing depth line under the embankment center, and studied the condition of laying insulation under , paved the influence of temperature characteristic of the anti-frost LO base berm , results show that: the anti-frost paved berm on the slope of soil under freezing depth of seasonal uplift to some extent , but the soil near the middle of the roadbed season The freezing depth has little effect [9]. Wang et al. [10] based on the existing frozen soil theory, thermodynamic principles and fluid mechanics theory, combined with the climatic characteristics of the Qinghai-Tibet Plateau and indoor and field test data, proposed a set of considerations for wind speed, radiation and evaporation. Factors and engineering appearance characteristics of the temperature field finite element numerical model and analysis method.

In the past, extreme boundary conditions were rarely considered, and the thickness design of the thermal insulation layer lacked a more scientific and reasonable method, which limited the practical application in frozen soil roadbed to a certain extent. Therefore, this paper uses ANSYS finite element analysis software to study the influence of the initial thermal field on the temperature distribution and maximum freezing depth of the foundation under extreme boundary conditions, and fully analyze the change process of the water field, temperature field and deformation field of the roadbed and the coupling mechanism, and explore the insulation thickness design of the insulation layer, to improve and perfect pile foundation in seasonal frozen soil area of power transmission engineering design, construction and operation and maintenance of great practical significance.

2. Modeling Process

2.1. Basic Assumptions
The temperature field and mechanical field of the soil around the foundation of the power transmission and transformation project in the frozen soil area are a complex problem affected by many factors. In order to establish the model, the following assumptions are made:

1. A two-dimensional simplified model is used to calculate the tower foundation and surrounding soil;
2. Ignore the contact thermal resistance between frozen soil layers;
3. It is assumed that any micro-element body is an isotropic linear elastic body;
4. The temperature in all directions at the same point of the soil is the same;
5. Ignore the thermal convection term and the ice-water phase transition process, and only consider the heat conduction.

2.2. Material Parameters and Modeling Process
Select the plane coupled field analysis unit. Analyze the model with tower base and choose plane13 element (this element is a 2-dimensional coupled field entity element, which has the function of limited coupling between two-dimensional magnetic, thermal, electrical, and structural fields. It is defined by 4 nodes, and each node can have 4 degrees of freedom), set the element degrees of freedom to have UX , UY , TEMP , AZ , and set the element properties to plane stress; to analyze the model without tower base, select plane 55 element (plane element or axisymmetric ring element for two-
dimensional heat conduction) Analysis. This unit has 4 nodes, and each node has only one degree of freedom - temperature).

According to the law of the influence of the ground surface temperature spreading below the surface, the calculation depth is selected to be 11.0 meters below the natural ground, and the calculation width is 4 times the base width. The width of the upper surface of the tower foundation is 2.0 m, the excavation foundation slope ratio is 1:0.75, and the cap slope ratio is 1:0.5. The excavation foundation is 5.0 m deep and the cap is 3.0 m high. The depths of the bottom layer of the first 1-5 soil layers are 1.5 m, 3.0 m, 5.0 m, 8.0 m, and 11.0 m respectively.

Among them, the thermal parameters, specific heat capacity and thermal conductivity, adopt temperature-related parameters, and are divided into two categories: frozen soil and unfrozen soil. Comprehensive consideration of “Hexi Power Grid 750 Line - Geotechnical Engineering Investigation Report” and “Frozen Soil Engineering Geological Investigation Specification GB50324-2014”, the specific values are shown in table 1. When inputting in ANSYS software, the specific heat capacity and thermal conductivity are set to four temperature points of -30, -1, 0, and 30 ℃, and the remaining temperature points are automatically calculated by interpolation. Among the mechanical parameters, the values of density and Poisson's ratio are shown in table 1.

### Table 1. Specific heat capacity and thermal conductivity of each material.

| Material            | Specific heat capacity (J/(kg·℃)) | Thermal conductivity (W/(m·℃)) |
|---------------------|----------------------------------|---------------------------------|
|                     | $C_{f}^{	ext{frozen soil}}$ | $C_{u}^{	ext{unfrozen soil}}$ | $\lambda_{f}^{	ext{frozen soil}}$ | $\lambda_{u}^{	ext{Unfrozen soil}}$ |
| Silt                | 832.9                           | 866.1                           | 0.46                           | 0.46                           |
| Silt                | 837.4                           | 737.7                           | 1.19                           | 0.95                           |
| Boulder             | 815.4                           | 718.3                           | 1.19                           | 0.95                           |
| Gravel              | 860.7                           | 758.2                           | 1.19                           | 0.95                           |
| Boulder             | 815.4                           | 718.3                           | 1.19                           | 0.95                           |
| Cap                 | 960                             |                                 | 1.28                           |                                |
| Insulation materials| 1050                            |                                 | 0.28                           |                                |
| Backfill materials  | 1050                            |                                 | 0.4679                         |                                |

For the value of elastic modulus, refer to Li Lei [6] and Wang Tiexing et al. [7]. The mechanical properties of frozen soil are expressed by the following equation 1, and the specific values are shown in table 1.

$$E = a_1 + b_1 |T|^m$$  \hspace{1cm} (1)

Among them, M is the non-linear index of elastic modulus, which is 0.6; $a_1$ and $b_1$ are test constants, and $b_1$ is equal to 0 when the soil is in a molten state. For silt, $a_1, b_1$ taken 30, 26; for fine sand, $a_1, b_1$ taken 62, 50; for gravel soil, $a_1, b_1$ taken 40, 45. The pile cap, heat insulation material and backfill material are all made of concrete with an elastic modulus of 30000 MPa.

The value of the coefficient of thermal expansion adopts temperature-related parameters and is divided into two categories: positive temperature and negative temperature. When the temperature is positive, it is considered as a porous medium, and it is considered as not swelling, which is 0; when the temperature is negative, it is converted by the void ratio according to the mixing of water and saturated soil.
3. Comparative Analysis of Results

3.1. Comparison of Thermal Protection Structure

First, the research compares the protection effects of different thermal protection structures. Three thermal protection structure forms with different protective layer thicknesses at the upper and lower ends of the cap are designed here, which are 1.5-0.5 m, 0.5-1.5 m, and 2-0 m.

The extreme conditions are selected for the study, that is, the surface temperature is -30 °C, the bottom soil temperature is 20 °C, and the thermal insulation coefficient of the thermal protection material is 0.28 W/(m·℃). Figure 1 is the temperature distribution cloud diagram calculated for each working condition. It can be clearly seen that the thermal protection material has a certain protective effect on the cap. In the cap part, the center of the bottom temperature is the lowest. To meet the thermal protection effect of the cap, we should ensure that the lowest temperature of the bearing platform is greater than the freezing point temperature (0 °C), so the subsequent analysis mainly focuses on the temperature change of the center line of the model.

![Figure 1. Temperature distribution cloud diagram for each working condition: (a) The original geological condition; (b) The 1.5-0.5 m structure; (c) The 0.5-1.5 m structure; (d) The 2-0 m structure.](image)

Figure 2 shows the temperature change of the model center line in each structure. It can be seen from the figure that the temperature value of the center line increases as the depth increases, and it changes linearly in the same material. Under this working condition, the freezing point temperature of the original formation model can be reached at a depth of -6.3 m, and the model with thermal protection materials can significantly increase the depth to the freezing point temperature. The depths of the bottom of the caps of the thermal protection structures of 1.5-0.5, 0.5-1.5, and 2-0 thermal protection structures are respectively -4.5 m, -3.5 m, -5 m, and their centerline temperatures are -
2.0 °C, -12.7 °C, 4.9 °C. Therefore, the thermal protection structure form 2-0 is the best, and the subsequent simulation calculation and analysis work adopt this structure form.

**Figure 2.** Three thermal protection structure forms and the model centerline temperature comparison diagram of the original formation.

3.2. The Influence of the Initial Thermal Field under Extreme Boundary Conditions

In this section, we choose a model with a thermal protection structure of 2-0 to systematically study the effect of different surface temperatures (-30, -15, -5, 0°C) on the results of thermal-mechanical coupling of the overall model. The bottom soil temperature of all models is 20 °C.

For the pile cap, not only the thermal protection of the pile cap structure must be realized, but also the deformation and stress requirements for the entire foundation. Figure 3 shows the Y- direction displacement at different depths and the X and Y- direction stresses at the upper and lower ends of the insulation layer when the surface temperature is -30 °C. It can be seen from figure 3 (a) that taking the centerline of the foundation as the boundary, the farther away from the centerline, the smaller the displacement in the Y direction. The excavation area of the foundation has the largest displacement in the Y direction when the depth is 0 m, and the maximum value is −10.6 mm; in figure 3 (b) can be seen, the insulating layer upper X direction is positive stress, across the insulation value of the maximum, gradually close to the middle position when, at first reduced and then increased tendency; lower insulation X The directional stress is negative, and the value is the smallest at both ends of the insulation layer. When the position gradually approaches the middle, it shows a rising trend.

**Figure 3.** Surface temperature -30 °C, (a) Y-direction displacement at different depths; (b) X and Y-direction stress at the upper and lower ends of the insulation layer.
4. Conclusion
In this paper, thermal insulation concrete is used as the thermal protection material of the tower base, and the extreme climatic environment in the Hexi area is used as the boundary condition. The research on the design optimization of the thermal insulation system thickness is carried out, and the thermal protection structure form and the thickness of the thermal insulation layer are determined. And binding site survey results and practical experience, typical theoretical analysis based on the analysis column bits thermal coupling effects and numerical simulation methods, studied the initial thermal heat shield structure of the field insulation properties, stress and deformation under extreme boundary where influences. It is of great practical significance to improve and perfect the design, construction, operation and maintenance of pile foundations for power transmission and transformation projects in seasonal frozen soil areas.

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