Analysis of Temperature, Stress and Displacement Distribution under Freeze-Thaw Considering the Influence of Initial Boundary and Insulation Layers

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Abstract. The freeze-thaw disaster in seasonally frozen soil area are challenging the operation safety of power transmission and transformation projects. The distribution of soil temperature and deformation laying below the foundation is significant to the soil stability in seasonally frozen soil area. The temperature distribution of the foundation is closely related to the external temperature, the thermal field of bottom boundary and the materials of insulation layers. In this paper, the typical tower foundation of 750 kV Gansu Hexi power grid project and the geological conditions of Shulehe area in Gansu Province were selected as the investigation site, and the theoretical analysis and numerical simulation methods are used to analyze the thermal-mechanical coupling considering different boundaries. The deformation, stresses and temperature changes of tower foundation and surrounding soil under different thermal protection structures were discussed. Through comparative analysis, it was found that the optimized structure can effectively improve the soil temperature in extreme environment, avoid frost heave, and meet the design requirements of bearing capacity.

Keywords: initial boundary condition, the insulation layers, the transmission and transformation engineering, the temperature field; the stress field

1. Introduction
In China, the power transmission and transformation project in Gansu Hexi region inevitably traverses a large area of seasonal frozen soil. In the seasonal frozen soil area, the sensitivity to environmental changes, the poor stability and the strong hydro-thermal coupling activities in soil threatened the construction and operation security of the transmission and transformation electrician engineering. Besides, under the influence of increased ground temperature, the frozen soil will also sink due to melting. The main hazard is the uneven settlement or overturning of the iron tower foundation. In fact, the problem of soil frost heave deformation is a multi-physics coupling problem.

Harlan (1973) proposed a coupled mathematical model of water and heat transfer in soil freezing process [1]. Konrad (1980) established a semi empirical model considering the empirical formula of frost heave, which provided a solution for the calculation of frost heave amount [2]. Gilpin (1985) regards ice as an undeformed rigid body with a linear stable temperature field inside [3]. Miao et al. (1999) established the water and heat coupling model of solid-liquid two-phase medium with phase change based on the nonlinear Burgers equation [4]. Li and Chen (2000) established the equilibrium equation of porous multiphase micro element, mass conservation equation and energy conservation equation of porous solid-liquid medium, and further analyzed the frost heave and thaw settlement of frozen soil [5]. Li (2016) deduced a two-dimensional theoretical model of temperature stress
deformation of frozen soil subgrade based on the theory of heat transfer and elastic-plastic deformation [6].

This paper mainly analyzes the influence of the boundary initial thermal field on the temperature distribution of the foundation and the maximum freezing depth, and fully analyzes the change process of the subgrade moisture field, temperature field and deformation field and its coupling mechanism. This research will be used to improve the design of transmission and transformation project power pile foundation, and ensure the construction and operation safety in seasonal frozen soil area.

2. Modeling Process

2.1. Basic Assumptions
In permafrost zone, the temperature field surrounding soil and mechanics field were influenced by many factors. In order to model the above behavior, several assumptions were listed as following:

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

The heat transfer process is a transient nonlinear problem, and the heat conduction differential equation is:

$$\frac{\partial}{\partial X} (k \frac{\partial T}{\partial X}) + \frac{\partial}{\partial Y} (k \frac{\partial T}{\partial Y}) + \frac{\partial}{\partial Z} (k \frac{\partial T}{\partial Z}) = \rho c \left( \frac{\partial T}{\partial t} \right)$$  \hspace{1cm} (1)

Where \(c\) is the specific heat capacity in units of J/(kg·℃); \(k\) is the thermal conductivity in units of W/(m·℃); \(T\) is the temperature in units of ℃; \(t\) is the time in units of s; \(X, Y, Z\) indicates the direction of heat transfer.

Based on the expressions of thermal stress and thermal strain, and the equilibrium equation of elastic material, the equilibrium differential equation of thermoelasticity can be obtained as:

$$\frac{\partial}{\partial X} (\frac{\partial e}{\partial X} + G \nabla^2 u - \beta \frac{\partial (\Delta T)}{\partial X}) + FX = 0$$  \hspace{1cm} (2)

$$\frac{\partial}{\partial Y} (\frac{\partial e}{\partial Y} + G \nabla^2 u - \beta \frac{\partial (\Delta T)}{\partial Y}) + FY = 0$$  \hspace{1cm} (3)

$$\frac{\partial}{\partial Z} (\frac{\partial e}{\partial Z} + G \nabla^2 u - \beta \frac{\partial (\Delta T)}{\partial Z}) + FZ = 0$$  \hspace{1cm} (4)

Wherein, \(FX, FY\) and \(FZ\) are the components of the volume force in the X, Y and Z axes; \(\mu\) is the Poisson's ratio; \(E\) is the modulus of elasticity; \(\Delta t\) is the temperature difference at two times; \(\alpha\) is the coefficient of thermal expansion; \(\varepsilon X, \varepsilon Y\) and \(\varepsilon Z\) are the thermal strains.

$$\lambda = \frac{\mu E}{(1+\mu)(1-2\mu)}$$  \hspace{1cm} (5)

$$G = \frac{E}{2(1+\mu)}$$  \hspace{1cm} (6)
2.2. Materials and Modeling Process

2.2.1. Define Unit Type. Firstly, the plane coupling field analysis unit were selected. The model of a tower foundation is analyzed using plane13 element (the element is a two-dimensional coupling field solid 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 have 4 degrees of freedom, which are UX, UY, TEMP, AZ. The element properties are defined as plane stress. The model without tower foundation choose plane55 element, which is a plane element or axisymmetric ring element for two-dimensional heat conduction. This unit has 4 nodes, and each node has only one degree of freedom - temperature).

2.2.2. Defining Material Properties. According to the propagation law of the surface temperature, the selected calculation depth was 11.0 meters below the natural ground, and the calculation width is 4 times the foundation width. The width of the upper surface of the tower foundation is 2.0 m, the excavation foundation slope is 1:0.75, and the platform slope is 1:0.5. The excavation foundation is 5.0 m deep and the platform is 3.0 m high. The bottom depths of the soil layers are 1.5 m, 3.0 m, 5.0 m, 8.0 m, and 11.0 m, respectively.

According to the "Hexi Power Grid Line 750 Geotechnical Engineering Investigation Report", the stratum is composed of silt, silty sand, round gravel, gravel sand, and round gravel. The part of the tower foundation is made of concrete. In figure 1, the pink is backfill and orange is heat protection material. The parameters required for the simulation include thermal and mechanical parameters. Thermal parameters include specific heat capacity and thermal conductivity; mechanical parameters include density, Poisson's ratio, elastic modulus and thermal expansion coefficient as shown in tables 1-4.

Among them, thermal parameters, specific heat capacity and thermal conductivity are both temperature-related parameters, which are divided into frozen soil and unfrozen soil. Comprehensively consider "Hexi Power Grid Line 750 Geotechnical Engineering Survey Report" and "Frozen Soil Engineering Geological Survey Specification GB50324-2014", the specific values are shown in table 1. When input in ANSYS software, the specific heat capacity and thermal conductivity are set to four temperature points -30, -1, 0, 30 °C, 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 2. In this study, five thermal conductivity parameters of 0.08, 0.13, 0.18, 0.23, and 0.28 W/(m·°C) were selected as the research parameters of the thermal protection material foam concrete.

**Table 1.** Values of specific heat capacity and thermal conductivity of each material.

| Material          | Specific heat capacity (J/(kg·°C)) | Thermal conductivity (W/(m·°C)) |
|-------------------|------------------------------------|---------------------------------|
|                   | $C_f$ permafrost $C_u$ unfrozen soil $\lambda_f$ permafrost $\lambda_u$ unfrozen soil |
| Silt              | 832.9                              | 0.46                            |
| Silty sand        | 837.4                              | 1.19                            |
| Boulders          | 815.4                              | 1.19                            |
| Gravel            | 860.7                              | 1.19                            |
| Boulders          | 815.4                              | 1.19                            |
| Platform          | 960                                | 1.28                            |
| Insulation materials | 1050                              | 0.08–0.27                      |
| Backfill material | 1050                               | 0.4679                          |

**Table 2.** Values of density and Poisson’s ratio of various materials.

| Material          | Density (kg/m$^3$) | Poisson’s ratio |
|-------------------|--------------------|-----------------|
| Silt              | 1887.8             | 0.3             |
| Silty sand        | 1887.8             | 0.3             |
| Boulders          | 1938.8             | 0.2             |
| Gravel            | 1836.7             | 0.2             |
| Boulders          | 1938.8             | 0.2             |
| Platform          | 2360               | 0.2             |
| Insulation materials | 1000               | 0.22            |
| Backfill material | 753                | 0.2             |

**Table 3.** Values of elastic modulus of each material.

| Elastic modulus (MPa) | $T$ (°C) |
|-----------------------|----------|
|                       | -30      | -20      | -10      | -5       | -1       | 0        | 30       |
| Silt                  | 230      | 186      | 133      | 98       | 56       | 30       | 30       |
| Silty sand            | 446      | 363      | 261      | 193      | 112      | 62       | 62       |
| Gravel                | 386      | 311      | 219      | 158      | 85       | 40       | 40       |
| Platform              | -        | -        | -        | 30000    | -        | -        | -        |
| Insulation materials  | -        | -        | -        | 30000    | -        | -        | -        |
| Backfill material     | -        | -        | -        | 30000    | -        | -        | -        |
The values of the coefficient of elastic modulus and thermal expansion, being used as temperature-related parameters, is divided into two categories: positive temperature range and negative temperature range. At positive temperature, it is considered to be a porous medium, which is considered to be non-swelling and the coefficient is 0. At negative temperature, it is converted from the pore ratio according to the mixing of water and soil. The specific values are shown in table 4.

| Materials    | e | $V_s$ | $V_v$ | Expansion Coefficient of Soil | Expansion Coefficient of Water | Expansion Coefficient of Water |
|--------------|---|-------|-------|-------------------------------|-------------------------------|-------------------------------|
| Silt         | 0.7 | 0.59  | 0.41  | 1.2E-3                        | 1.3E-4                        | 7.59E-4                       |
| Silty sand   | 0.7 | 0.59  | 0.41  | 9E-6                          | 1.3E-4                        | 5.88E-5                       |
| Gravel       | 0.6 | 0.625 | 0.325 | 5E-6                          | 1.3E-4                        | 5.19E-5                       |
| Platform     | -   | -     | -     | -                             | -                             | -                             |
| Insulation   | -   | -     | -     | -                             | -                             | -                             |
| Backfill material | -   | -     | -     | -                             | -                             | -                             |

3. Results and Discussion

3.1. Central Line Temperature Distribution

In this paper, the model with a thermal protection structure of 2-0 is selected to study the effect of the bottom soil temperature (15, 20°C) on the overall model. The surface temperature of all models is -30°C as an extreme condition.

Figure 2 shows the temperature distribution clouds of different models. (a) Initial state; (b) Thermal protection structure form 2-0.

Figure 2 is the temperature distribution cloud after calculation of each working condition. It can be clearly seen that the thermal protection material has a certain protective effect on the platform. In the platform part, the center of the bottom temperature is the lowest. The results indicated that the minimum temperature of the platform part is greater than the freezing point temperature (0°C), which meet the requirement of thermal protection of the platform. Then, the subsequent analysis is mainly based on the temperature change of the center line of the model.

Figure 3 shows the central line temperature under different operating conditions. The results show that the depth at which the freezing temperature is reached when the bottom soil temperature is 15°C is
lower than that at 20°C, indicating that the initial temperature boundary of the bottom layer has a significant influence on the depth of the frozen soil.

In order to prevent frost heave settlement of the foundation, a thermal insulation layer is laid on the surface of the foundation. As the results shown in Fig 4, when the temperature of subsoil is 15°C, the thermal conductivity of the thermal protective material is smaller, and the better the effect of thermal protection. Corresponding to thermal protection material 0.08, 0.13, 0.18, 0.23, 0.28 W/(m·°C), the central line temperature of the bottom of the platform is 1.4, -0.3, -1.5, -2.5, -3.3°C. The analysis result shows that when the boundary temperature of the bottom layer is 15°C, the thermal conductivity of the thermal protection material needs to be reduced.

![Figure 3](image-url)

**Figure 3.** The central line temperature with different bottom soil temperature and different thermal protection materials.

3.2. Foundation Stress and Displacement Clouds

Figure 4 is the cloud diagram of the deformation and stress distribution corresponding to each working condition. The results show that the thermal protection material with a thermal conductivity of 0.08 W/(m·°C) can achieve the thermal protection of the bearing platform at lower soil temperature of the bottom layer.

![Figure 4](image-url)
Figure 4. Deformation and stress distribution of thermal protection structure form 2-0 at surface temperature -30 °C, bottom soil temperature 15 °C, thermal protection material thermal conductivity 0.08 W/(m·°C): (a) X- direction displacement; (b) X- direction stress; (c) Y- direction displacement; (d)Y- direction stress; (e) Total displacement; (f)Total stress.

The bearing platform not only need to achieve thermal protection requirement of the bearing platform structure, but also there are requirements for deformation and stress for the entire foundation. Figures 4 and 5 are shown for different depths (0, -1.5, -3.0, -5.0, -8.0 m) in the Y -direction displacement and X- , Y direction stress of top and lower ends of insulation structure. From Fig. 5, the Y-direction displacement in different depths are horizontally symmetric. The foundation excavation region at a depth of 0 m having a maximum Y -direction displacement. At a depth of -8.0 m, the Y direction reach to the minimum displacement. At the other depth (-1.5, -3.0, -5.0 m), the Y direction displacement changing trend and values are basically the same. The maximum Y- direction displacement is -10, -10 , -9 mm at a depth of -8.0 m. In addition, the displacement of the bottom of the bearing platform in the Y direction is -8 mm, and there is no obvious uneven settlement of the foundation. As can be seen from the right column of figure 5, the thermal insulation materials of structure model 2-0 have similar stress trends in the X and Y directions at the upper and lower ends. The maximum X- direction stress of the thermal protection structure is 31 MPa.
Figure 5. Displacement and stress at different depths: (a) The displacement value of 2-0 structure in Y direction; (b) The internal stress of 2-0 structure.

4. Conclusion
In this paper, thermal insulation concrete is used as the thermal protection material of the tower foundation, and the climate and environment of Hexi region are used as the boundary conditions to carry out a study on the optimization of the thickness design of the thermal insulation system. Based on site survey results and practical experience, a theoretical analysis and numerical simulation on the thermal-mechanical coupling effects were performed. Considering the temperature on bottom layer and the thermal conductivity of the material, the temperature, strain and stress distribution are calculated and analyzed in detail by ANSYS software. Through comparison, it is found that the initial thermal field at the boundary has an significant influence on the temperature distribution and the analysis of the maximum freezing depth. A suitable structural form is used to effectively raise the temperature of the soil in extreme environments, avoid frost heave, and meet the design's bearing capacity requirements.

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