Prediction of temperature field of embankment in permafrost region of Qinghai Tibet railway

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Abstract. Temperature field distribution of Qinghai-Tibet railway is important for analyzing embankment stability. Based on the finite element method, the analysis model of temperature field is developed for predicting the changes in embankment thermal field in the following 40 years. The results show that the permafrost will degenerate to seasonally frozen soil.

1. Introduction

As the third-largest permafrost country in the world, the distribution area of Permafrost in China is 7.29 million square kilometres. Frozen soil has an extremely close relationship with human survival and development [1,2]. With the continuous advancement of China western development plan, engineering construction in cold regions is increasing rapidly. A variety of water conservancy projects, road projects, industrial and civil buildings, tunnel projects, etc., marked by major cold-zone projects such as the Qinghai-Tibet highway, the Qinghai-Tibet railway, West-East Power Transmission, Golmud-Lasa oil pipeline, communication optical cable and the planned South-to-North Water Diversion Project, is in full swing. Permafrost is highly sensitive to the change of foundation temperature, and the roadbed is built for later engineering construction. Therefore, the hydrothermal condition of the railway embankment in permafrost area has a direct impact on the natural soil under the embankment, especially on the stability of the embankment.

In view of the above, based on the monitoring data of the embankment temperature field in the Ando test section of Tanggula Mountain and the actual situation of the embankment field in permafrost area of Qinghai-Tibet Railway, the finite element calculation model of the slope embankment temperature field was established to predict and analyze the variation state of the embankment temperature field in the next 40 years in the Ando test section of Qinghai-Tibet Railway.

2. Site profile

2.1. Test section conditions

The Ando test section is located in the Gaalbuqu River Valley district, 70km south slope of Tanggula Mountain, in the permafrost region in the hinterland of the Qinghai-Tibet Plateau, with an average
altitude of more than 4,800 meters, and the route goes through the ridge section. In this region, the summer is short, the winter is long, and there is no obvious spring and autumn as the transition season. The annual average ground temperature is around -0.3℃, which belongs to the extremely unstable area of permafrost. The permafrost thickness in the Ando test section is about 15m [3], so the permafrost is extremely vulnerable to the destruction caused by temperature rise and human activities.

2.2. Introduction of the test section
In this paper, the temperature field prediction analysis was carried out for a section of the Anduo test section, as shown in Fig.1. It can be seen from the figure that the embankment is a slope embankment, which is different from the horizontal embankment. The overall shape of the slope embankment is asymmetrical.

3. Simulation of embankment temperature field

3.1. Temperature field calculation model
According to the actual situation of embankment site in permafrost area of Qinghai-Tibet Railway, the calculation model of embankment temperature field is assumed as follows:

1) Each layer of embankment and foundation soil is assumed to be homogeneous;
2) The water content of the stable section of roadbed is relatively small, and its water content is generally unchanged;
3) Assume that there is no other boundary for water supply and drainage;
4) In the process of soil freeze-thaw cycle, the heat conduction term is much larger than the thermal convection term. Therefore, convection, mass migration, water evaporation heat consumption and other effects were ignored in the calculation, which only considered the heat conduction of soil framework and medium water and ice-water phase change [3,4].

In summary, the heat balance control equation for the transient temperature field problem can be expressed as follows:

\[
\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\lambda_z \frac{\partial T}{\partial z})
\]

In the formula: \( \rho \) - Soil density; \( T \) - Soil temperature; \( C \) - Specific heat of soil; \( \lambda \) - Thermal conductivity of soil. According to the different freeze-thaw conditions, the specific heat and thermal conductivity of soil can be expressed as shown in equations (2) and (3):
The interface follows the nonlinear energy conservation condition, because the relevant thermodynamic parameters related to the railway embankment soil, including specific heat capacity and thermal conductivity, are not fixed, but constantly change with the increase or decrease of temperature. Therefore, the above equations involve complex nonlinear problems, and the analytical solutions cannot be obtained from mathematics. Galerkin method was used to obtain its numerical solution by numerical analysis [4]. In the finite element method, its calculation formula is as follows:

\[
[M]\left\{\frac{\partial T}{\partial t}\right\} + [K]\{T\} = \{F\}
\]

\[
M_{ij} = \sum \int_{\Omega} \alpha C N_i N_j d\Omega
\]

\[
K_{ij} = \sum \int_{\Omega} \alpha \left( \frac{\partial N_i}{\partial x} \frac{\partial N_j}{\partial x} + \frac{\partial N_i}{\partial y} \frac{\partial N_j}{\partial y} + \frac{\partial N_i}{\partial z} \frac{\partial N_j}{\partial z} \right) d\Omega + \sum \int_{\Gamma} \alpha T_u N_j d\Gamma
\]

\[
F_i = \sum \int_{\Gamma} \alpha T_u N_i d\Gamma
\]

In the formula: \(N_i, N_j\)-The form function of a unit.

3.2. Thermal boundary condition analysis

3.2.1. Boundary conditions.

According to the observation data of Qinghai-Tibet Plateau and boundary layer principle, it is assumed that the top boundary condition of the model is the first type of boundary condition. However, the parameter value of the boundary condition changes correspondingly with the constant change of time. The temperature of natural surface (AB and EF edges) was fully taken from references [4-6], varying as follow formulas:

\[
f(t) = -0.4 + 12.2 \sin\left(\frac{2\pi}{365} t + \frac{\pi}{2}\right) + \frac{2.6t}{365 \times 50}
\]

The temperature on the BC side of the embankment slope (sunny slope) changes as follows:

\[
f(t) = 1.1 + 16 \sin\left(\frac{2\pi}{365} t + \frac{\pi}{2}\right) + \frac{2.6t}{365 \times 50}
\]

The temperature on the CD side of the top of the embankment varies according to the following law:

\[
f(t) = 1.5 + 18 \sin\left(\frac{2\pi}{365} t + \frac{\pi}{2}\right) + \frac{2.6t}{365 \times 50}
\]

The temperature on the DE side of the embankment slope (shaded slope) varies according to the following law:
\[ f(t) = -0.5 + 18 \sin(\frac{2\pi}{365}t + \frac{\pi}{2}) + \frac{2.6t}{365 \times 50} \]  

The boundaries on both sides of model take the second type of boundary conditions, and AM and FN can be regarded as adiabatic boundaries: \( \frac{\partial T}{\partial n} = 0 \).

The ground temperature gradient at the bottom boundary MN of model: \( \frac{\partial T}{\partial n} = 0.08^\circ C/m \).

### 3.2.2. Initial conditions.

The temperature variation of the upper boundary AF of the foundation soil is a trigonometric function as shown in equation (9), which reflects the temperature condition of natural soil layer in the section prior to the construction of the railway roadbed. This study calculated the 50 years according to the above, and utilized the temperature results after 50-year as the initial condition to analyze and calculate the temperature field in the next 40 years in order to ensure the stability of initial temperature conditions.

\[ T = -0.4 + 12.2 \sin(\frac{2\pi}{365}t + \frac{\pi}{2}) \]  

#### 3.3. Selection of physical thermal parameters

The physical and thermal parameters of the soil layers in the Anduo section of Qinghai-Tibet Railway roadbed are shown in Table 1.

| Materials                              | \( \rho \) / kg·m\(^{-3}\) | W / % | \( \lambda_f \) / J·m\(^{-1}\)·°C\(^{-1}\)·d\(^{-1}\) | \( \lambda_u \) / J·m\(^{-1}\)·°C\(^{-1}\)·d\(^{-1}\) | \( C_f \) / J·kg\(^{-1}\)·°C\(^{-1}\) | \( C_u \) / J·kg\(^{-1}\)·°C\(^{-1}\) | \( L \) / J·kg\(^{-1}\) |
|---------------------------------------|-----------------|------|---------------------------------|---------------------------------|-----------------|-----------------|-----------------|
| Filler                                | 2000            | 10   | 225504                          | 165801.6                        | 892             | 1149            | 9714.3          |
| Silty clay                            | 1920            | 20   | 124850                          | 97632                           | 1043.9          | 1309.4          | 31406.3         |
| Mudstone sandwiched with sandstone    | 2100            | 10   | 147248                          | 127008                          | 1026            | 1166            | 18850.0         |

PS: The subscripts \( f \) and \( u \) in the table represent frozen and thawed states respectively.

#### 3.4. Temperature field model validation

In order to examine the validity of temperature field analysis model, it was compared and analyzed with the field-monitored A-A cross-sectional ground temperature data from the literature [6], as shown in Fig.2.
Fig.2. Comparison of field monitoring data and simulation values of temperature field

From the field monitoring results, it could be seen that the ground temperature gradually tended to fixed value -0.3°C in that the natural upper limit was about 3.0m and below the natural upper limit, belonging to the permafrost high temperature extremely unstable area. The thickness of perennial permafrost was about 15m. From the figure, we could see that the ground temperature gradually tended to -0.45°C in that the calculation natural upper limit was 3.4m and below the natural upper limit, which was slightly lower than the monitoring results, but also belonged to the high temperature extremely unstable permafrost region, and the permafrost thickness was about 17m. The above analysis showed that the measured results of soil ground temperature were relatively close to the calculated results, indicating the effectiveness of established ground temperature prediction model.

3.5. Temperature field calculation results

Fig.3 explained the ground temperature contours when the embankment section reaches the maximum melting depth in the 10th, 20th, 30th and 40th years. Fig.4 predicted the temperature-depth curves for the 5th and 40th years at the central section of roadbed. It can be clearly seen from the above figure that permafrost still exists in the centre of the roadbed in the first 20 years. The artificial upper limit of permafrost on the roadbed decreased as the number of years increases, meanwhile the lower limit also showed an upward trend year by year, which indicates that the permafrost on the Qinghai-Tibet Railway was degrading year by year. It was predicted by 30 year that after the permafrost area degraded annually the permafrost at the foot of the roadbed's positive slope degraded into seasonal permafrost from perennial frozen soil, with only part of the permafrost area at the foot of embankment shady slope; The perennial permafrost was expected to degrade into seasonal permafrost by 40 year, with a freezing depth of about 6.9m. In general, climatic conditions have a greater impact on the strong influence on the high-temperature extreme unstable permafrost. It is possible that the permafrost section below the Qinghai-Tibet Railway embankment will completely degrade to seasonal permafrost under the overall trend of global warming.
4. Conclusions

Based on a background of the Anduo test section of the Qinghai-Tibet Railway, this paper used the finite element method to establish a calculation model of the embankment temperature field, predicted the changes of embankment temperature field in the Anduo section of Qinghai-Tibet Railway. The following conclusions were drawn:

(1) The validity of the ground temperature prediction model was demonstrated by comparing the measured and calculated results of the soil ground temperature. It was proved that the computational model of this scheme can provide more reliable prediction data for future studies.

(2) The finite element calculations illustrated that the perennial permafrost in the Anduo test section would gradually degrade in the first 20 years and it would have completely degraded into seasonal permafrost by the 40th year under conditions of 0.03°C annual warming increase on the Tibetan Plateau. In addition, the maximum melting depth of the roadbed at different times and the variation of annual average ground temperature were simulated more intuitive over time.

(3) Climatic conditions have a strong influence on high-temperature and extremely unstable permafrost, which may lead to complete degradation of perennial permafrost in the event of global warming.
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