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An engineering evaluation index of thermal asymmetry in subgrade and its optimal design in cold regions

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ABSTRACT

In cold regions, thermal budget between ground and atmosphere rebalances after linear engineering is constructed. The local surface morphology and strike of subgrade could cause asymmetric thermal boundary conditions, although most of conventional subgrades is geometrically symmetric. The asymmetric thermal boundaries bring the sunny-shady slope effect, which is investigated in most studies by comparing the temperatures difference between symmetric positions. This is one-dimensional analysis when modeling a two-dimensional subgrade profile, which cannot well describe the asymmetric geothermal field, not to mention the uncertainty of the coupling effects of thermal conditions and filling modes due to asymmetry. This study proposes an engineering evaluation index, thermal static moment (TSM). The bigger TSM value is, the more asymmetric the geothermal field is. Based on this method, the difference and distribution characteristics of temperature profile were analyzed. An optimal subgrade filling mode was proposed based on TSM evaluation. The TSM difference was smaller for optimized mode than that of conventional mode, so the thermal regime of the optimal filling mode was better.

1. Introduction

The large-scale linear engineering has been widely constructed in cold regions, such as railway, highway, oil pipeline and electrical power lines. These engineering shows a difference in both thermal regime and changing process due to local morphology and strike under various engineering geology, geological and hydrogeological conditions. As for the same subgrade, there exists temperature difference under two slopes. This phenomenon is called sunny-shady slope effect in frozen subgrade. In most cases, when filling the embankment in cold regions, the mechanical and thermodynamic analysis is mostly performed on subgrade profile that is generally filled symmetrically in both geometry and filling materials. In the mechanics and thermodynamic analysis, a typical two-dimensional profile was chosen to estimate the stability of subgrade. But in the conventional analysis, the common subgrade was symmetric in both material and geometry; however, the asymmetric thermal boundaries and symmetry geometry caused the asymmetric temperature distribution and corresponding changing process, and the asymmetric deformation in symmetric positions, e.g., asymmetry geothermal field, moisture migration and cryogenic phenomenon asymmetry, thawing settlement and frost heave (Esch, 1983). In permafrost regions, this kind of asymmetry in geothermal regime could result in offset of permafrost table (Zarling et al., 1983). In seasonally frozen regions, the difference of frozen regime appeared at sunny and shady slopes, which would cause distress and damage in cold regions engineering.

Many researches have been carried out on the stability of subgrade in cold regions. Chen et al. (2006) analyzed the thermal difference and its influence on the degree of engineering stability in the Qinghai-Tibet Railway, and then put forward two suggestions for eliminating this sunny-shady slope effect by studying its radiation mechanism. Liu et al. (2014) investigated this phenomenon along the Harbin-Dalian Passenger Dedicated Line (HDPDL) in deep seasonal frozen regions, and found the thermal differences in coarse-grained soil subgrade slope. Qin et al. (2015, 2016a, 2016b) studied the albedo and shading boards at the embankment slope, and found that in permafrost regions in the Northern Hemisphere, raising the southern side-slope albedo can remedy the differential solar absorption across the embankment. It is not necessary to paint the surface white to increase the side-slope albedo, and a group of non-white pigments can be alternatively used with high reflectivity. Yaling et al. (2007, 2009, 2010, and 2014) forecast the differences in both ground temperature and deformation in Qinghai-Tibetan plateau considering the sunny-shady slope effect and gave a thorough analysis of how the sunny-shady slope impacts on the thermal and deformation stability of the highway embankment in warm

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permafrost region. Lai et al. (2004a, 2006) found from a series of experiments carried out on crushed-rock layers with open and closed boundaries that with upper boundary covered, the heat transfer from the lower area to the upper is by means of the natural convection and the thermal conduction among crushed rocks.

Niu et al. (2003a) carried out an experiment for adjusting the temperature in sunny and shady slope by duct-ventilated measurement and found the ground temperature of the roadbed decreases during the second freezing-thawing circle, though it increases during the first circle, and the geothermal field shows a better symmetric regime in the subgrade. There are also experiments and numerical simulation in the Qinghai-Tibet Railway to verify this (Yu et al., 2002; Lai et al., 2004b; Su et al., 2004; Niu et al., 2003b; Wang and Dou, 2004; Sheng et al., 2005). Goering and Kumar (1996), and Goering, (2003) defined this subgrade as a duct-ventilated roadbed. Its theory and design method were discussed by some researchers (Goodrich, 1978, Kudryavtsev et al., 1974, Smith and Rise Borough, 2002; Zhang et al., 2011). Berg and Aitken (1973) suggested to change the slope color to adjust the radiation difference. Kondratyev (1996) suggested setting shading board and Feng (2002) made a site monitoring in the Qinghai-Tibet Railway for the effectiveness of this measurement. Above all, researchers had proposed a number of methods and measurements to reduce this effect.

Based on the asymmetric thermal boundary condition and the sunny-shady slope effect, using the concept of static moment, this study suggested a new evaluation index and method, thermal static moment, and verified it by monitoring in-situ data. For symmetric subgrade with asymmetric thermal boundaries, the authors suggested an optimal filling mode for subgrades in cold regions. By changing the types of asymmetry of subgrades with A/B group of filling materials, the asymmetry of geothermal field was decreased, and the sunny-shady slope effect was partially eliminated.

2. Evaluation method

One of the frequently used method evaluating the thermal asymmetry and instability of roadbed was qualitative or semi-quantitative analysis. The common methods for evaluating geothermal filed distribution and changing process generally used two symmetric points from boreholes under the roadbed shoulders, which was one-dimensional analysis. This method can represented the thermal regime, but for the two-dimensional profile of frozen roadbed, the difference of temperature caused by filling materials would result in uneven deformation. The spot or linear difference in the symmetric position cannot reflect the behaviors of thermal regime and the sunny-shady slope effect in a whole subgrade profile, especially in the asymmetric roadbed structure with different filling materials. Thus, a concept of thermal static moment was introduced based on the principle of geometry and material science. Then we discussed and verified both the whole computing process and results.

Fig. 1 shows the common types of grid unit that used in analysis. The definition of thermal static moment can be seen in Fig. 2. Fig. 3 shows the grid map for roadbed after meshing. The bottom boundary is the depth of mean average ground temperature (MAGT), the width from

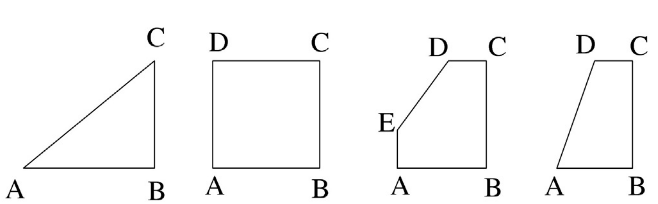

Fig. 1. The geometric unit type.

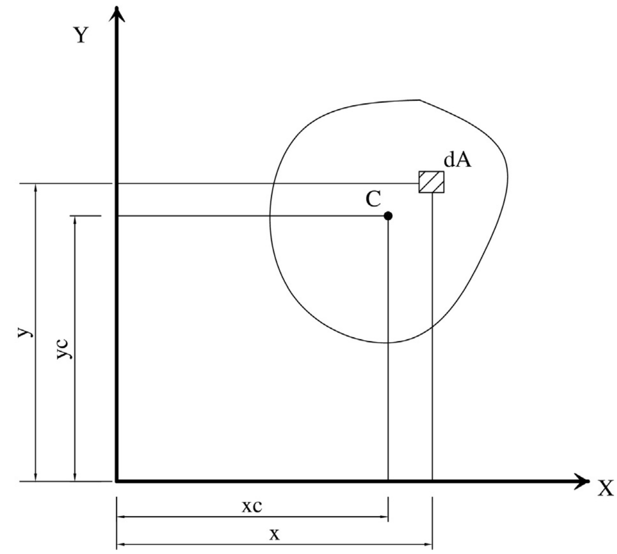

Fig. 2. The sketch map of thermal static moment.

the toe of slope to the left or right boundary is equal to the depth of MAGT. The unit shape and calculation principle can be seen in Figs. 1 and 2. The areas for computation is A, and X, Y are the coordinate axis in the plane. In the coordinate system (x, y), we could find an arbitrarily micro unit dA, and there is an integral definition throughout the area A.

$$S_x = \int_A y dA, S_y = \int_A x dA, \tag{1}$$

where S_x and S_y are the static moment in X and Y axis for area A. In this example,

$$S_{Tx} = \int_A \overline{T_A} y dA, \quad S_{Ty} = \int_A \overline{T_A} x dA, \tag{2}$$

$$\overline{T_A} = \frac{\int_A T_s dS}{A} \tag{3}$$

$$\overline{T_A} = \frac{T_1 + T_2 + T_3 + T_4 + \ldots T_n}{n} \tag{4}$$

From the principle of material mechanics we can conclude that the TSM is highly relevant to the coordinate system. The TSM maybe either positive or negative, even equal to zero, which depends on the reference coordinates. The dimension of TSM is T^1L^3. In engineering practice, the size of grid mesh can be in arbitrary scale. Note that the size scale of both micro unit and the arm of temperature is consistent.

For the static moment theory, the coordinates of the thermal center of geometry are $(\overline{x}, \overline{y})$:

$$\overline{x} = \frac{\int_A \overline{T_A} x dA}{\int_A \overline{T_A} dA}, \quad \overline{y} = \frac{\int_A \overline{T_A} y dA}{\int_A \overline{T_A} dA} \tag{5}$$

The equations for TSM in two directions can be derived as follows:

$$S_{Tx} = \int_A \overline{T_A} dA \cdot \overline{y}, \quad S_{Ty} = \int_A \overline{T_A} dA \cdot \overline{x} \tag{6}$$

It should be noticed that the centroid and thermal center of geometry does not necessarily coincide when the sunny-shady slope is included. There is probably a deviation or symmetric axial rotation. This quantitative difference can be used as an index for thermal asymmetry and to evaluate the sunny-shady slope effect.

In the meanwhile, a reasonable interpolation method is required for extending the monitoring data to the whole profile of roadbed. In this