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Research Paper

Thermal stability investigation of wide embankment with asphalt pavement for Qinghai-Tibet expressway based on finite element method

Tao Ma [a,*], Tao Tang [a], Xiaoming Huang [a], Xunhao Ding [a], Yao Zhang [a], Deyu Zhang [b]

[a] School of Transportation, Southeast University, 2 Sipailou, Nanjing, Jiangsu 210096, China
[b] School of Engineering and Architecture, Nanjing Institute of Technology, 1 Hongjing Road, Nanjing, Jiangsu 211167, China

HIGHLIGHTS

- Expressway construction seriously disturb the thermal regime of permafrost.
- Wider embankment leads to worse thermal regime and thermal stability.
- Raising embankment height results in larger differential thawing settlement.
- Combined protective measures should be used for wide expressway.

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ABSTRACT

This study aims to analyze the thermal regime and stability of wide embankment in permafrost regions to facilitate the future construction of Qinghai-Tibet Expressway. Based on finite element method, thermo-hydro-mechanical coupling model was built to investigate the thermal stability and thawing settlement of embankments. The validity was verified by field observed data from Qinghai-Tibet Highway. Based on numerical analysis, the temperature field, thawing depth and thawing settlement of embankments with different width were investigated. The influences on the thermal stability of embankments by different protective measures such as raising height of embankment, setting crushed stone layer in embankment, setting Expanded Polystyrene (EPS) layer in embankment and setting the combination of crushed stone layer and EPS layer in embankment were evaluated. It was found that embankment construction has serious disturbance on the thermal stability of ground permafrost. Meanwhile, larger embankment width leads to worse thermal stability of ground permafrost and more serious thawing settlement of embankment. Increasing the embankment height can improve the thermal regime of embankment, however, the thawing settlement and differential thawing settlement of embankment get worse with bigger embankment height. Setting crush rock layer or EPS layer can improve the thermal stability of embankment, however, the improvement is limited for wide embankment with width exceeding 26 m. The combination of crush rock layer and EPS layer has the best protective effects on the thermal stability of wide embankment, however, the differential thawing settlement under pavement still needs to be paid attentions to.

1. Introduction

According to the National Expressway Network Plan of China, the Qinghai-Tibet Expressway (QTE) will be constructed on the Qinghai-Tibet Plateau in the near future [1]. Since asphalt mixture and pavement has been commonly used for expressway and their performance has been well proved [2–4]. The QTE will be constructed with asphalt pavement. However, the performance of asphalt mixture and pavement are easy to be affected by the environment especially the ambient temperatures [5–7]. More importantly, known as "black pavement", the high heat absorption capacity of asphalt pavement is a critical threat to the thermal stability of permafrost in the Qinghai-Tibet Plateau [8–10]. Thus, although the construction of QTE is of great significance, it is not easy to build a high quality expressway across the more than 500 km continuous permafrost regions on the Qinghai-Tibet Plateau [11]. Like the current Qinghai-Tibet Highway, one major difficulty that the construction of QTE confronting with is the destruction effect of QTE on the fragile ecological environment of

* Corresponding author.
E-mail address: matao@seu.edu.cn (T. Ma).

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permafrost regions [12,13]. Soils experiencing periodic freezing and thawing may exhibit dramatically different behaviors (such as strength, stiffness, or compressibility), depending on their thermal state [14–16]. A series of studies on the Qinghai-Tibet highway and railway indicated that continuous thawing of underlying permafrost is the main reason to cause the embankment settlement [17–19]. Many efforts have been made to estimate the deformation and settlement of embankments associated to frozen soil in permafrost regions [20–23]. It is proved that the permafrost is very sensitive to climate change because its strength decreases dramatically with the increase of temperature. Due to thawing of ground permafrost, the embankment tends to lose its bearing capacity resulting in geohazards such as thawing subsidence and active-layer detachment failure. To solve the issues of thawing settlement and permafrost degradation, a number of measures have been investigated to improve the thermal stability of permafrost embankment, which include raising the embankment height, insulating materials, thermosyphons, awnings, crushed-rock embankment, air cooling ducts, etc. [24–28]. All these methods were proven to be effective in cooling permafrost embankment by engineering practices.

It is noticed that, most of existing permafrost embankments of current highways and railways are narrow embankments with width no more than 10 m. Meanwhile, the expressways usually have wide embankment with width within the range of 24.5–45 m, which are approximately 2.5–4.5 times of the current embankment width of Qinghai-Tibet Highway. Compared with narrow embankment, the intensity of heat absorption in wide embankment will be much higher and it is more difficult for the heat to dissipate outward the wide embankment. Thus, the QTE construction will experience more serious technical barriers, especially the thermal degradation and thawing settlement of permafrost and embankment. However, current researches and cooling methods mainly are based on the narrow embankment.

Thus this paper focused on the thermal stability of wide embankment. A thermo-hydro-mechanical coupling model was built based on ABAQUS and verified by field data to evaluate the thermal regime and thawing settlement of permafrost embankment. The influences by embankment width on the thermal stability of embankments were analyzed. Improving effects on the thermal stability of embankments by different protective measures, including raising height of embankment, setting crushed stone layer in embankment, setting Expanded Polystyrene (EPS) layer in embankment and setting the combination of crushed stone layer and EPS layer in embankment, were evaluated. The findings can be used to facilitate the future construction of Qinghai-Tibet Expressway.

2. Numerical modeling

Previous studies proved that the thawing settlement of soil was closely related to its temperature field and phase change [29]. Thus, based on a typical section of Qinghai-Tibet Highway, a two-dimensional thermo-hydro-mechanical coupling model with phase change was developed to investigate the temperature field and thawing settlement of different embankments. The numerical analysis were carried out through a sequential approach, in which the temperature field was modeled as a pure heat transfer analysis and then the obtained temperature field was used to drive phase change to calculate the thawing settlement.

2.1. Geometric model

As shown in Fig. 1, the numerical calculating section consisting of embankment and natural ground was determined according to a typical section of Qinghai-Tibet Highway with geometric dimensions of 3 m in height, 10 m in width and 1:1.5 for the gradient of side slope. To minimize the size effects, the selected geometric domain for computation was extended for 20 m wide from the each-side toe of the side slope and 20 m deep from the original ground surface. The embankment along with the natural ground was divided into four layers: layer I is the embankment mainly consisting of gravel soil; layer II with thickness of 2.3 m mainly consists of pebbly clay; layer III with thickness of 1.6 m mainly consists of gravel loam; and layer IV with thickness of 16.1 m mainly consists of strong erosion mudstone. During numerical modeling, to analyze the influences by the width and height of embankment on the thermal regime of embankment and natural ground, the width and height of the embankment will vary from 10 m to 50 m and 2 m to 7 m, respectively.

Two protective measures, which are crush rock layer and Expanded Polystyrene insulting layer, were used in this study. The crush rock layer is composed of crushed stones with size of 6–8 cm. The EPS insulting layer is made of Expanded Polystyrene which is a lightweight and porous material with low thermal conductivity, high heat resistance and high strength. While the crush rock layer was mainly used to promote the heat convention between embankment and environment, the EPS layer was mainly used to resist heat flow from environment to embankment. As shown in Fig. 2, during the numerical modeling, the Expanded Polystyrene (EPS) insulting layer with thickness of 0.1 m was set at the depth of 1 m below the pavement surface and the crush rock layer with thickness of 1.5 m was set at the depth of 0.5 m above the natural ground surface.

2.2. Modeling theory and parameters

2.2.1. Governing equations and constitutive model

No heat consumption was assumed as moisture evaporation in soil, and the two-dimensional heat-fluid coupling equations were proposed based on energy and mass conservation theory [30,31], which can be described as follows:

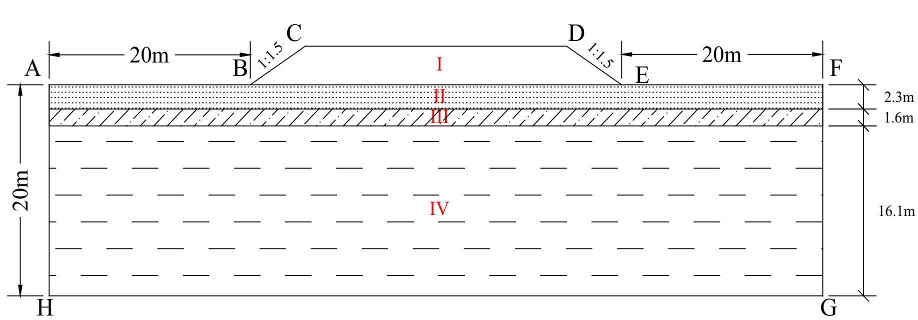

Fig. 1. Geometric sketch of the computational model.