Analysis of the Embankment Stability in Permafrost Regions based on Double Strength Reduction Finite Element Method

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Abstract. In order to study the embankment stability in permafrost regions, the vertical deepening and horizontal extension of the thaw bulb under the embankment in permafrost regions have been calculated and analyzed based on the double strength reduction finite element method. The vertical depth of the thaw bulb has less impact on the location of longitudinal cracks, and greater impact on the size of cracks on the embankment surface. Moreover, the deeper the vertical depth of the thaw bulb is, the larger the size of cracks becomes. The horizontal extension of the thaw bulb not only impacts on the location of longitudinal cracks on the embankment surface, but also impacts on the size of cracks. There is a critical length for the horizontal extension of the thaw bulb, where the probability of longitudinal cracks is the greatest. When the length is smaller than the critical length, the probability of longitudinal cracks increases with the length increasing; when the length is greater than the critical length, there will be no longitudinal cracks, but the whole embankment tilts to the sunny slope.

1. Introduction

In permafrost regions of Qinghai-Tibet plateau, after the construction of asphalt pavement, the thermal exchange between the atmosphere and the Earth’s surface was changed, and the original thermal equilibrium was broken [1,2]. As a result, the annual thermal absorption of the embankment surface was greater than the thermal dissipation. Especially in high-temperature permafrost regions, the soil thaw depth in summer may be greater than that in winter from the beginning of embankment construction [3,4]. After a freezing-thawing cycle, the phenomenon of disconnection may occur in permafrost, forming a non-frozen thawed interlayer between the permafrost table and the active layer base. With the increase of freezing-thawing cycles and the thermal accumulation in the stratum, the thawed interlayer expands year by year and forms a thaw bulb finally [5-7]. Due to the thawed of permafrost in the thaw bulb, the region presents a weak feature [8]. The development of the thaw bulb...
leads to a series of embankment diseases, such as longitudinal cracks, embankment cracks, shoulder slippage and lateral tilt [9-12]. Therefore, the formation and development of the thaw bulb is the main cause of embankment diseases.

The development of the thaw bulb is mainly divided into two aspects. First, with the increases of the operation time, the lower limit of the thaw bulb keeps decreasing, the thaw depth keeps deepening, and the area keeps enlarging. Second, due to the shady-sunny slope effect, as the embankment moves from east-west to north-south, the thaw bulb shifts from the sunny slope to the center of the embankment gradually [13,14]. The thaw depth of the sunny slope is greater than that of the shady slope, resulting in uneven settlement of embankment. When the failure stress is greater than the soil tensile strength, the longitudinal cracks may occur on the embankment surface, which may destroy the embankment stability [15,16]. The development characteristics, the evolution trend and the relation to the embankment stability of the thaw bulb have been concerned by researchers and embankment maintenance technicians [17,18]. At present, there are relatively few reports about the relationship between the thaw bulb and the embankment stability at home and abroad [19]. Most studies focused on the field monitoring of ground temperature and deformation of the embankment in permafrost regions, and it is concluded that the embankment diseases are serious in the section with the development of thaw bulb [20]. The relationship between the thaw bulb and the embankment stability is generally described qualitatively, and the quantitative analysis is not enough. The double strength reduction finite element method is proposed in the study of stability of side slope, landslide, foundation, tunnel and highway [21-26]. This method takes the varying degrees of the cohesion and friction angle into account, the cohesion and friction angle are divided by different reduction factors according to the soil actual failure process, the slope failure is judged by numerical calculation non convergence and plastic penetration area [27-30]. However, the application of this method to the analysis of the embankment stability in permafrost regions is rarely reported.

In this paper, the double strength reduction finite element method is carried out by ANSYS software. The DP1 (Mohr circumscribed circle criterion) is transformed into DP4 (new circle criterion), and the shear strength parameters are reduced after transformation [31]. The vertical deepening and horizontal extension of the thaw bulb under the embankment in permafrost regions are calculated and analyzed based on the weak feature of the thaw bulb, and the embankment stability in permafrost regions is studied.

2. Calculation model and calculation method

2.1. Calculation model

Considering the shady-sunny slope effect on the both sides of embankment, the whole embankment cross-section is taken as the research object. According to the research results of Pei J [32], the thaw bulb under the embankment was simplified into a triangle. The calculation model are shown in figure 1, the embankment height is 3.5m, the embankment width is 7.5m, the grade of side slope is 1:1.5, the depth of the model is 30m below the natural ground, and the width of the model is 61m. The computational area is divided into seven parts, where part A1 and A2 are weathered mudstone in the permafrost layer, part A3, A4 and A5 are gravel silty clay, part A2 and A4 form a triangular thaw bulb (That’s: the left side is the sunny slope, and the right side is the shady slope), part A6 is silty clay in the seasonal active layer, and part A7 is embankment filler that is sandy gravel soil.
2.2. Calculation method

Based on the weak feature of the thaw bulb, the double strength reduction finite element method is carried out by ANSYS software. The default of ANSYS software is DP1 (Mohr circumscribed circle criterion), and the calculated safety factor is usually larger. On the contrary, the safety factor calculated by DP4 (new circle criterion) is reasonable under plane strain condition [33]. Therefore, it is necessary to convert DP1 criterion into DP4 criterion, using the following two steps:

2.2.1. Convert DP1 criterion into DP4 criterion. The conversion formula from DP1 criterion to DP4 criterion is:

\[ F_2 = \frac{\sqrt{3(\cos^2 \phi_0 F_1^2 + \sin^2 \phi_0 - \sin \phi_1)^2 - 12 \sin^2 \phi_0}}{12 \cos^2 \phi_0} \]  

(1)

where, \( F_1 \) - the reduction factor of DP1; \( F_2 \) - the reduction factor of DP4; \( \phi_0 \) - the actual friction angle of soil.

Let \( F_2 = 1 \), the implicit solution of \( F_1 \) is:

\[ 9 F_1^2 \cos^2 \phi_0 + 10 \sin^2 \phi_0 - 6 \sin \phi_0 \sqrt{\cos^2 \phi_0 F_1^2 + \sin^2 \phi_0} - 12 = 0 \]  

(2)

\( F_1 \) can be obtained by substituting \( \phi_0 \) into equation (2). The actual shear strength parameters of soil \( \phi_0 \) and \( c_0 \) are divided by \( F_1 \), the cohesion \( \phi_1 \) and friction angle \( c_1 \) of soil under DP4 criterion can be obtained. According to the borehole data measured in BeiLu-River of Qinghai-Tibet Railway [34], the calculation parameters of soil after transformation are shown in table 1.
Table 1. Calculation parameters of soil after DP1 is converted to DP4

| Domain | Type            | \( \varphi_0 \) (°) | \( c_0 \) (kPa) | \( F_1 \)   | \( \varphi_i \) (°) | \( c_i \) (kPa) |
|--------|-----------------|----------------------|-----------------|------------|----------------------|-----------------|
| A7     | Sandy gravel    | 30                   | 35              | 1.4        | 21.2                 | 24.82           |
| A6     | Silty clay      | 20                   | 28              | 1.3        | 15.3                 | 21.54           |
| A3\A5  | Gravel silty clay | 39                  | 150             | 1.5        | 6                    | 25              | 96.15           |
| A4     | Thaw bulb 2     | 20                   | 1.4             | 1.3        | 15.3                 | 1.08            |
| A2     | Thaw bulb 1     | 20                   | 1.6             | 1.3        | 15.3                 | 1.23            |
| A1     | Weather mudstone| 39                   | 1300            | /          | 39                   | 1300            |

2.2.2. Double strength reduction. The shear strength parameters \( c_i \) and \( \varphi_i \) are divided by the cohesion reduction factor \( F_c \) and the friction angle reduction factor \( F_\varphi \). According to the literature of Zheng Y et al. [21-24,32], the reduction ratio adopted is \( F_c = 1.4F_\varphi \), and the parameters after reduction input program can be calculated. Because the properties of weather mudstone in permafrost are less affected by the external environment, it is not reduced and its initial physical and mechanical state is retained. Only the soil layers above the permafrost are subjected to double strength reduction.

3. Calculation result

3.1. The influence of thaw bulb on the embankment stability

In order to study the influence of thaw bulb on the embankment stability, two kinds of conditions are calculated and analyzed by double strength reduction finite element method. First, there is a thaw bulb under the embankment. Second, there is no thaw bulb under the embankment. The thaw bulb refers to the thawing of weather mudstone layer and gravel silty clay layer, and the physical and mechanical properties of the two conditions are the same except the thaw bulb. Then, the shear strength parameters of soil are calculated at a ratio of \( F_c = 1.4F_\varphi \). When the thaw bulb is not taken into account in figure 2, both sides of the embankment appear the circular arc plastic penetration area. As shown in figure 3, when there is a thaw bulb under the embankment sunny slope, a plastic penetration area basically parallel to the sunny slope appeared. When the plastic penetration area occurs in both conditions, the safety factor \( F \) of considering thaw bulb is 2.16 times higher than that of without considering thaw bulb. It can be seen that the thaw bulb has great influence on the embankment stability. It is of great significance to study its existence and form.
3.2. The influence of vertical deepening of thaw bulb on the embankment stability

After the construction of embankment in the permafrost regions, the lower limit of the thaw bulb decreases with the increase of the operation time, and longitudinal cracks on the embankment surface gradually form with the deepening of the thaw depth.

As shown in figure 4, the horizontal displacement at all points on the embankment surface is positive. It shows that the thawed of permafrost under the sunny slope leads to the whole embankment tilts to the sunny slope, but the tilt degree of all points on the embankment surface is different. When the vertical depth of the thaw bulb is 3.4m, the horizontal displacement difference between the left and right shoulder of the embankment surface is 4.4mm, and the maximum horizontal displacement of the embankment surface is 3.5 times that of 1m. Therefore, the difference of horizontal displacement between different points on the embankment surface is the main reason for the formation of longitudinal cracks on the embankment surface. The variation trend of horizontal displacement on the embankment surface shows that the change under all conditions has experienced three stages. First, the horizontal displacement within 0-2m of the embankment surface at a stable stage with a higher value. Second, the horizontal displacement within 2-4m of the embankment surface at a mutation stage, and the deeper the thaw bulb is, the more serious the mutation is. Third, the horizontal displacement within 4-7.5m of the embankment surface is at a stable stage with a lower value. Therefore, the location of longitudinal cracks may be in the horizontal displacement mutation region within 2-4m on the embankment surface.

As can be seen from figure 5, the strain on the embankment surface first increases and then decreases. With the vertical deepening of the thaw bulb, the maximum strains are about 3m from the left shoulder of embankment. Moreover, the maximum strain at a vertical depth of 3.4m is 5 times that of 1m. Therefore, the vertical depth of the thaw bulb has less impact on the location of longitudinal cracks, and greater impact on the size of cracks on the embankment surface. Moreover, the deeper the vertical depth of the thaw bulb is, the larger the size of cracks becomes.
3.3. The influence of horizontal extension of thaw bulb on the embankment stability

The difference of solar radiation, residual water at the foot of embankment and vegetation coverage on both sides of embankment makes the embankment have a shady-sunny slope effect [13]. As the embankment moves from east-west to north-south, the thaw bulb shifts from the sunny slope to the center of embankment gradually. The thaw depth of the sunny slope is greater than that of the shady slope, resulting in uneven settlement of the embankment. When the failure stress is greater than the soil tensile strength, the longitudinal cracks may occur on the embankment surface, which may destroy the embankment stability. The horizontal extension of the thaw bulb is that the right side of the simplified triangle extends to the left shoulder of embankment (LSE), the center of embankment (CE), and the right shoulder of embankment (RSE).

As shown in figure 6, when the horizontal extension of the thaw bulb extends to the center of embankment, the horizontal displacement difference between the left and right shoulder of embankment surface is 2.8mm, and the maximum horizontal displacement of the embankment surface is 2 times that of the right shoulder of embankment. When the horizontal extension of the thaw bulb extends to the right shoulder of embankment, the horizontal displacement of the whole embankment surface is about 3.15mm, and the whole embankment tilts to the sunny slope. It shows that there is a critical length for the horizontal extension of the thaw bulb, where the probability of longitudinal cracks is the greatest. When the length is smaller than the critical length, the probability of longitudinal cracks increases with the length increasing; when the length is greater than the critical length, there will be no longitudinal cracks, but the whole embankment tilts to the sunny slope.

As can be seen from figure 7, the strain on the embankment surface first increases and then decreases. As the increase of the horizontal extension of the thaw bulb, the location of the maximum strain moves to the right of embankment gradually. So the possible location of longitudinal cracks moves to the right of embankment gradually. When the thaw bulb extends to the right shoulder of embankment, the maximum strain of embankment decreases. This phenomenon may be caused by the extension of the thaw bulb to the edge of embankment, resulting in increased dispersion of the thaw bulb, reducing the weakening effect of the thaw bulb on the soil. When the thaw bulb extends to the center of embankment, the maximum strain is 0.0086, 2.7 times that when it extends to the right shoulder of embankment. Therefore, the horizontal extension of the thaw bulb not only impacts on the location of longitudinal cracks, but also impacts on the size of cracks on the embankment surface.
4. Conclusion

In order to study the embankment stability in permafrost regions, the vertical deepening and horizontal extension of the thaw bulb under the embankment in permafrost regions have been calculated and analyzed based on the double strength reduction finite element method. The vertical depth of the thaw bulb has less impact on the location of longitudinal cracks, and greater impact on the size of cracks on the embankment surface. Moreover, the deeper the vertical depth of the thaw bulb is, the larger the size of cracks becomes.

The horizontal extension of the thaw bulb not only impacts on the location of longitudinal cracks, but also impacts on the size of cracks on the embankment surface. There is a critical length for the horizontal extension of the thaw bulb, and the probability of longitudinal cracks is the greatest. When the length is smaller than the critical length, the probability of longitudinal cracks increases with the length increasing; when the length is greater than the critical length, there will be no longitudinal cracks, but the whole embankment tilts to the sunny slope.

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