Analysis of creep properties of soft soil subgrade using gravel piles based on Modified Burgers model

Feng rui Zhang [1, a] , An nan Jiang [2,b] , Xing-cang Yao[3,c] , Zhan ping Song [4,d]

[1]Highway and Bridge Institute of Dalian Maritime University, Dalian, 116026, China;

[2]Highway and Bridge Institute of Dalian Maritime University, Dalian, 116026, China;

[3]China Construction Eight Engineering Division.CORP.LTD Dalian branch company, No.237,Gorky road, Dalian, 116021,China;

[4]School of Civil Engineering, Xi'an University of Architecture and Technology, Xi'an, 710055, China;

[a]email:15104585257@163.com,[b]email:jiangannan@163.com

Keywords: Soft soil subgrade; creep model; water content; temperature; creep properties.

Abstract. The paper takes Donggang expressway as the engineering background, based on the Burgers model, considering the effects of temperature and water content on the creep properties of rock, the creep damage constitutive model of low temperature rock is established, which can reflect the instantaneous elastic deformation, decay creep, steady creep, accelerated creep and the plastic properties. Using the software FLAC^{3D} to simulate creep properties of soft soil subgrade at Donggang during freezing period, the results show that: reinforcement effect of pile on the soft soil subgrade is quite obvious, the creep settlement and creep rate of soft subgrade treated by gravel pile are obviously reduced. The creep property of watery soil is smaller than that of dry soil, and the lower the temperature, the higher the freezing degree of the rock and soil, the property of creep is the less obvious. Comparative analysis of in-situ monitoring and numerical calculation, the correctness and accuracy of result from numerical calculation can be verified.

Introduction

In recent years, with the rapid growth of highway construction, a lot of high grade highways have been built in the coastal soft soil area, the stability of subgrade receives more and more attention. Soft soil subgrade is characterized in high water content, strong compressibility, low shear strength and poor permeability, showing obvious rheological properties. Therefore, after the completion of the main consolidation of the subgrade, it will produce a "long" creep settlement, endangering the safety of the road traffic.

Creep property of soft soil subgrade is studied widely by researchers[1-5]. Although the research on creep property of soft soil subgrade has made considerable progress, but little attention has been paid on the effects of variation in temperature and water content, the creep property of the soft soil subgrade in the northern coastal areas will be affected by the low temperature and water content. Therefore, this paper takes Donggang expressway as the engineering background, based on the Burgers model, a creep constitutive model considering the low temperature and water content is proposed, using the software FLAC ^{3D} to simulate creep characteristics of soft soil subgrade at Donggang, the results have guiding significance for the prevention of the settlement of the soft soil subgrade in the northern coastal areas.

Brief Introduction of engineering

Donggang highway is located in the south of Liaoning Province, the line is north-south direction, about 17 km in length. Muck and mucky soil are widely distributed in the area, about 3-10m in thickness. The rock and soil layer has the characteristics of high water content, strong compressibility, low strength and long consolidation time. The region is a warm temperate semi-humid continental monsoon climate, the annual average temperature is about 7.8℃,the lowest temperature is about -30℃, the maximum frozen soil depth is about 105cm, and rainy season usually come from June to September.

A creep constitutive model considering the low temperature and water content

In this paper, combined with the KBurgers-MC model is established in the reference[6], considering the influence of low temperature and water content on the creep properties of rock[7-8], the creep damage constitutive model of low temperature rock is established, which can reflect the instantaneous elastic deformation, decay creep, steady creep, accelerated creep and the plastic properties.

Based on the Burgers model, the creep constitutive model considering the low temperature and water content is established, THB model for short, as shown in Figure 1. The THB creep model is composed of plastic body, Maxwell body, Kelvin body and nonlinear damage body in series. Where η_1, η_2, E_1, E_2 are parameters related to the water content. σ_{M-C} is yield stress based on Mohr-Coulomb criterion.
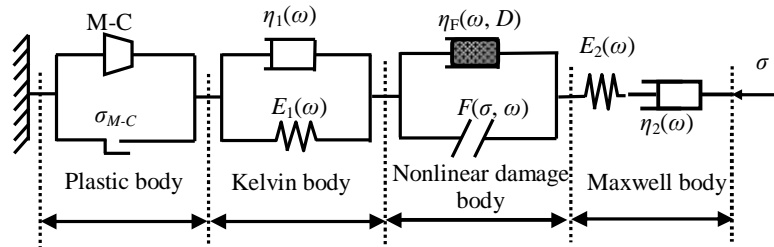

Fig. 1 THB creep damage model

Assuming that the material is isotropic damage, the damage law of each parameter is the same. $A'(w,t)$ is as follows:

$$A'(w,t) = A_0 - A_0 \cdot H(w,T) \tag{1}$$

The influence function of temperature and water content on rock creep can be obtained by experiment, as shown in the formula (8).

$$H(T,w) = (T+7)10^{-3} + \frac{0.1015 - 2.645w + 17.227w^2}{1 - 23.474w + 213.371w^2} \tag{2}$$

The constitutive equations of the THB model are described as follows

（1）When $\sigma < \sigma^*$,

$$e_{ij} = \frac{S_{ij}}{2G_2'} + \frac{S_{ij}}{2h_2'}t + \frac{S_{ij}}{2G_1'}\left[1 - \exp\left(-\frac{G_1'}{h_1'}t\right)\right] + \langle F(s,w)\rangle \, e_F \tag{3}$$

In the formula: " ' "is the variable related to the water content of ω, σ^* is the general yield stress calculated by the Mohr-Coulomb yield criterion.

（2）When $\sigma \geq \sigma^*$,

$$\dot{e}_{ij} = \dot{e}_{ij}^K + \dot{e}_{ij}^M + \dot{e}_{ij}^F + \dot{e}_{ij}^P \tag{4}$$

Kelvin body:

$$S_{ij} = 2G_K' e_{ij}^K + 2h_K' \dot{e}_{ij}^K \tag{5}$$

Maxwell body:

$$\dot{e}_{ij}^M = \dot{e}_{ij}^H + \dot{e}_{ij}^N = \frac{\dot{S}_{ij}}{2G_M'} + \frac{\dot{S}_{ij}}{2h_M'} \tag{6}$$

Nonlinear damage body:

$$e_F = \begin{cases} 0 & , \ \langle F(s,w) \rangle = 0 \\ \dfrac{s}{a(w)h_3(w)}\left[e^{a(w)t} - 1\right] & , \ \langle F(s,w) \rangle = 1 \end{cases} \tag{7}$$

Plastic body:

$$\dot{e}_{ij}^P = l \frac{\partial g}{\partial s_{ij}} - \frac{1}{3}\dot{e}_{vol}^P d_{ij} \tag{8}$$

In the formula:

$$\dot{e}_{vol}^P = l \left[\frac{\partial g}{\partial s_{11}} + \frac{\partial g}{\partial s_{22}} + \frac{\partial g}{\partial s_{33}}\right] \tag{9}$$

In the plastic mechanics, it is generally assumed that the spherical stress does not produce plastic strain, so the spherical stress rate of whole model can be written,

$$\dot{s}_m = K'\left(\dot{e}_{vol} - \dot{e}_{vol}^P\right) \tag{10}$$

The Cvisc model provided by FLAC^{3D} is a new model of Burgers model under Mohr-Coulomb criterion. The source code of Cvisc model is the second development blueprint, and the THB dynamic link library file is written in Microsoft Visual C ++ 6.0, using the software FLAC ^{3D} to calculate it.

Numerical analysis of soft soil subgrade

Establishment of three-dimensional numerical model

This paper takes the K2+250 section of the first contract section of Donggang expressway as the engineering background, three-dimensional numerical model of soft soil subgrade is established, the total of 8063 units, 16596 nodes. The depth of stratum is 30m; the width of stratum is 200m, the thickness of stratum is 5m. The upper layer is flow- soft- plastic silty clay, about 10m in thickness; the middle layer is wholly-weathered rock, about 8m in thickness, the lower layer is strong-weathered rock, about 12m in thickness. The filling height of roadbed is 5m, the upper width is 40m, the bottom width is 55m,and the slope is 1:1.5. Pipe gravel pile is applied at the bottom of the

embankment, the diameter of the pile is 0.4m, the length is 10m, the spacing is 1.5m. The bottom of the model is the fixed boundary, the left and the right are bounded in the x direction, and the front and back are bounded in the y direction, the top of the model is free boundary, as shown in Figure 2. According to construction of Donggang soft soil subgrade in freezing period, using THB creep model for numerical computation.
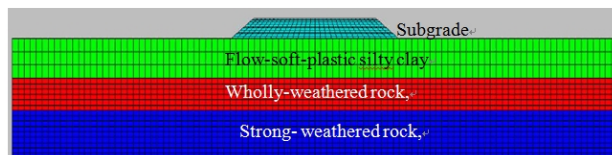

Fig. 2 Three-dimensional numerical model and stratum distribution

Selection and determination of calculation parameter

Most of the physical parameters required for the model are measured in field and experiment. Assuming that the soil layer is homogeneous and isotropic, the parameters of stratum are shown in Table 1. The parameters of the gravel pile are shown in Table 2.

Table 1 The parameters of stratum

Stratum	K (GPa)	den ($kg \cdot m^{-3}$)	fric (°)	coh (kPa)	*ten* (kPa)	η_1 (GPa·h)	η_2 (GPa·h)	E_1 (GPa)	E_2 (GPa)	α
Silty clay	0.040	2000	20	42	105	14.6	10	0.102	0.159	0.02
Wholly-weathered	0.023	2100	25	18	90	9.1	8.52	0.125	0.132	0.03
Strong- weathered	0.21	2150	30	80	121	112.8	204.8	1.294	0.95	0.05

Table 2 The parameters of gravel pile

Nme	den (kg·m-3)	E *(GPa)*	μ	cs_sk (N·m^{-2})	cs_scoh (N·m^{-1})	cs_sfric (°)
Pile	2540	50	0.15	1.3×10^{11}	1×10^{10}	15

Analysis of the results

Influence of pile on subgrade settlement

Before construction, the two cases of adding piles and without pile are calculated numerically, and the creep curves of the subgrade are shown in Figure 3.
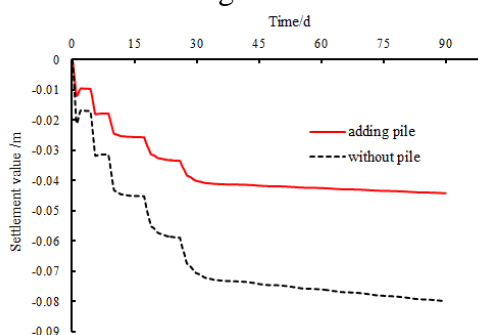

Fig. 3The creep curves of the subgrade

The figure 3 shows that, during the embankment construction, the deformation of subgrade without pile is far greater than the deformation of subgrade with piles, the settlement value reaches -73mm after the completion of the filling subgrade. After 30d, the creep rate of the subgrade remains stable, but the creep value continues to increase, and finally reaching -82mm. The numerical results show that: the deformation of the subgrade without pile continuously increases, and the deformation is too large. After subgrade by adding piles, the deformation of the subgrade decreases during the filling period, the final deformation is controlled at -42mm, the creep is controlled effectively and tended to be stable.
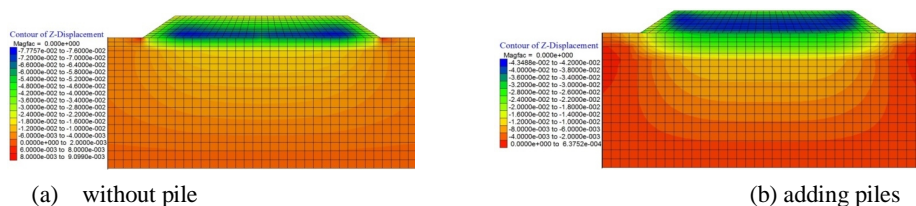
(a)　without pile　　　　　　　　　　　　　　　　　　(b) adding piles

Fig. 4 Displacement of the piles applied and not applied at *t* = 86 d

Figure 4 is the vertical displacement of the piles applied and not applied at t = 86 d. As seen in the figure (a), the maximum displacement is located at the bottom of the subgrade, the local displacement is larger, and the contour of the settlement is "oval concave ". A uplift at the slope toe of subgrade, which is due to the extrusion caused by filling. As seen in the figure (b), the maximum settlement value is extended to the whole subgrade, the maximum value is about 40mm, which is mainly due to the supporting force of the pile to prevent the overall settlement of the subgrade. The shape of the contour approximately becomes " square concave ", and the slope toe of subgrade is not uplift.

Effect of water content and temperature on creep of Subgrade

The settlement of soft soil subgrade is not stopped immediately after the completion of the filling, because the temperature and the water content of each month is different, the subgrade shows different laws of creep settlement. To find the best construction scheme, the creep settlement of soft soil subgrade under different water content in 1~3 months is simulated, as shown in figure 8.
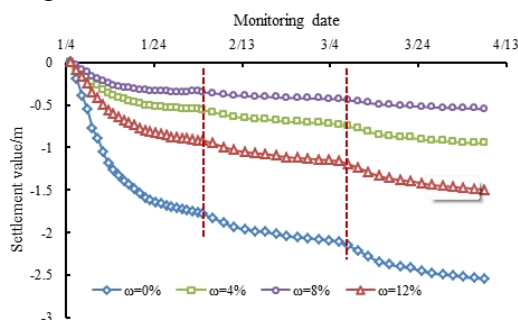

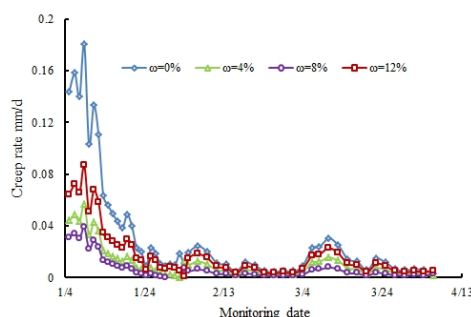Fig.5 Creep curves of subgrade with different water content　　　Fig.6 Creep rate curves of subgrade with different water content

As can be seen from Figure 5, the cumulative creep of the soil in the dry state is the largest among the four cases, and the cumulative sedimentation in the three months is 2.5 mm. The creep property of watery soil is smaller than that of dry soil, this is because the liquid water in soft soil is frozen into ice under low temperature. The gap between the soil particles is filled with ice crystals, increasing the effective contact area between particles. The ice crystal bears the support force and cohesion of some particles, which increasing the overall strength of the subgrade, so the creep rate and the creep settlement are greatly reduced. When the water content exceeds a certain limit, the phenomenon of frost heaving of Subgrade that occur under low temperature, resulting in the overall strength is reduced, so that the creep rate and creep, leading to the decrease of the whole strength, so that the creep rate and creep value increase.

Figure 6 is the creep rate curves of subgrade with different water content, the results show that the creep settlement rate of subgrade increases rapidly in the first 10 days of January, and the creep value is larger. The creep rate in February is slightly faster than that at the end of January, the creep rate in March is also faster than that in February. From the research[9-10], temperature in January is

-9℃, temperature in February is-7℃, temperature in March is -2℃, the lower the temperature, the

slower the creep rate. Because rock and soil particles are more dense after contraction with the decrease of temperature, the increase of "bite force" between the particles leads to the enhancement

of the physical and mechanical properties of the rock and soil.

Comparative analysis of numerical calculation and in-situ monitoring

To master the change of the creep settlement of soft soil subgrade, creep settlement monitoring is required during subgrade construction. Observation scheme: three settlement observation instruments are set up on the K2 + 250 section of subgrade, and setting three displacement observation piles on both sides of the subgrade.

Comparative analysis of in-situ monitoring and numerical calculation, the correctness and accuracy of result from numerical calculation can be verified, as shown in Figure 7.
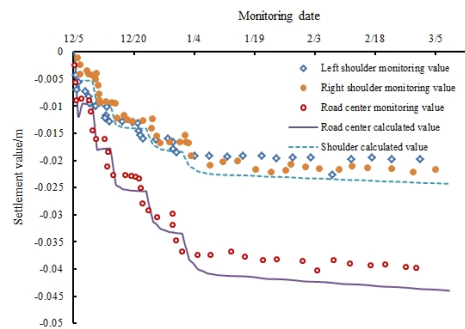

Fig.7 Comparison of in-situ monitoring and numerical calculation

It can be seen from the figure 7, the settlement of the center of the road is the largest, creep value is 44mm in 3 months, creep value of the shoulder is 24mm. The monitoring values are in good agreement with the calculated values, indicating the accuracy of numerical calculation

Conclusions

（1）Based on the Burgers model, the creep damage constitutive model of low temperature rock

is established, which can reflect the instantaneous elastic deformation, decay creep, steady creep, accelerated creep and the plastic properties, describing the influence of temperature and water content on the creep properties of rock(THB model). The THB dynamic link library file is written in Microsoft Visual C ++ 6.0, using the software FLAC ^{3D} to calculate it.

（2）Study the influence of pile on creep properties of soft soil subgrade, numerical results show

that: the creep settlement and creep rate of soft subgrade treated by gravel pile are obviously reduced, the shape of the contour approximately becomes " square concave ".

(3) The water content and temperature have a significant impact on the creep properties of soft

soil subgrade, the creep property of watery soil is smaller than that of dry soil, when the water content exceeds a certain limit, the phenomenon of frost heaving of Subgrade that occur under low temperature, resulting in the overall strength is reduced, leading to the creep rate and creep value increase. And the lower the temperature, the higher the freezing degree of the rock and soil, the property of creep is the less obvious. The monitoring values are in good agreement with the calculated values, indicating the accuracy of numerical calculation.

Acknowledgements

References

[1] Jiang Zong bin, Jiang An nan, Shi Jing. Chinese Journal of Geotechnical Engineering, 2013, 35(2): 346–351.(in Chinese)

[2] Li Ming fei, Dou Yi hua. Inner Mongolia Petrochemical Industry, 2008(15) : 30-32. (in Chinese)

[3] Tan Ru jiao, Jiao Yu jie, Xu Wen jie. Hydrogeology & engineering geology, 2015,42(4):67-73. (in Chinese)

[4] Zhang Jing xian, Yang Ai wu, Zhang Yan, et al.Journal of Tianjin Institute of Urban Construction,2010,16(2): 102-106. (in Chinese)

[5] Li Qing yuan, Ren Jian xi. Journal of Xi'an University of Science and Technology, 2009, 29: 712–717. (in Chinese)

[6] Huang Ming, Liu Xin rong, Deng Tao. Rock and Soil Mechanics, 2012, 33(6):1876-1882. (in Chinese)

[7] Yang Geng she, Pu Yi bin, Ma Wei.. Journal of Experimental Mechanics, 2002, 17(2): 220–226. (in Chinese)

[8] Chen Wei zhong, Tan Xian jun, Dan Dan, et al. Chinese Journal of Rock Mechanics and Engineering, 2011, 30(7): 1318–1336. (in Chinese)

[9] Liu Dong yan, Jiang Hai fei, Li Dong sheng, et al. Journal of Central South University (Science and Technology), 2014, 45(6): 1916–1923.

[10]Jiang Hui fei, Liao Shuhua. Chinese Journal of Agrometeorology , 2004, 25(3): 1-4.