Numerical simulation of creep settlement for high railway foundations based on the UH model considering time effect

Wei Chen i), Naidong Wang ii)*, Hongye Yan iii), Feng Chen iv), Qianli Zhang v)

i) Master Student, State key laboratory of high-speed railway track technology, No. 2, Daliushu Road, Haidian District, Beijing, 100081, China;
ii) Lecturer, School of Transportation Science and Engineering, Beihang University, No. 37, Xueyuan Road, Beijing, 100083, China;(*corresponding author, E-mail: wangnd@buaa.edu.cn)
iii) Associate professor, Academy of Railway Sciences Corporation Limited, No. 2, Daliushu Road, Haidian District, Beijing, 100081, China;
v) Professor, Academy of Railway Sciences Corporation Limited, No. 2, Daliushu Road, Haidian District, Beijing, 100081, China.

ABSTRACT

The high-speed railway has strict restrictions on the settlement of the roadbed, and the settlement value must not exceed 15mm. In the process of calculating the settlement of high-speed railway subgrade, the impact of soil creep should be considered. In the creep calculation, the calculation parameters should have practical physical meaning. Therefore, based on the UH model considering time effect, the secondary development of ABAQUS software is realized, and the finite element simplified model of the high-speed railway in a section near Qufu East Station is established. The creep settlement of the points on the surface of the natural roadbed under the high-speed railway is concave curve of distribution. With the change of time, the creep growth rate of each point becomes slower and slower, and the creep settling curve shows a tendency of gradual flattening.

Keywords: high-speed railway, creep settlement; UH model considering time effect, numerical simulation, finite element

1 INTRODUCTION

The smoothness of high-speed railway is an important safety guarantee for trains during high-speed driving, and there are strict restrictions on the settlement of high-speed railway subgrade. In the calculation of subgrade soil deformation, the creep properties of soil are very important. Whether to consider the creep properties of soil will not only result in significantly different calculations, but also directly affect the safety evaluation of the whole project. Therefore, the study of creep settlement of high-rail natural subgrade soil has very important engineering significance.

Creep deformation refers to the process that soil deformation increases continuously with time under the action of constant stress, which is related to the long-term performance of actual engineering. Therefore, creep deformation occupies an important position in soil mechanics. Since the 3rd international conference on soil mechanics and foundation engineering in 1953, the study of soil creep characteristics has attracted extensive attention from scholars at home and abroad. Wang et al. (2011) comprehensively analyzed and summarized the current studies on soil creep characteristics and creep models, and put forward the concept of soil equivalent deformation process on this basis. Oliveira et al. (2013) conducted indoor creep tests of 1-dimension and 3-dimension for soft soil, and analyzed its long-term disaster reduction characteristics accordingly. Yin et al. (2019) proposed a simplified calculation method of one-dimensional compression settlement that takes into account creep of viscous soil. This method has simple form and clear parameters, and is suitable for various stress-strain states and complex loading, unloading and reloading situations of viscous soil.

Based on the UH model considering the time effect, a three-dimensional analysis model of high-speed railway foundation was established by the large-scale finite element software ABAQUS, and creep deformation of high-speed railway foundation soil was
calculated and analyzed.

2 SIMPLIFICATION OF MODEL

A high-speed railway in a section near Qufu East Station uses a ballastless track. The embankment is filled 3.5m high. The foundation is reinforced with CFG piles with a length of 20m. The piled concrete composite foundation structure is used in the reinforcement area. Figure 1 is a simplified schematic diagram of the calculation model. In order to improve the calculation speed and efficiency, the area between the two dotted lines in Figure 1 is used for modeling in this paper with the method of symmetric simplification. Figure 2 is the calculation model of the high-speed railway subgrade and CFG pile composite foundation.

![Fig. 1. Simplification of model.](image1)

![Fig. 2. Schematic diagram of calculation model.](image2)

3 CALCULATION MODEL OF CREEP SETTLEMENT

At present, the methods for predicting post-construction settlement of soil in actual engineering mainly include hyperbolic method, Hoshino method, Asaoka method and so on. The hyperbolic method is an empirical derivation method that assumes that the average sedimentation rate decreases in a hyperbolic form. The calculation result is larger than the measured value, which is safe for engineering, but requires a long time settlement observation. The Asaoka method is mainly used to determine the final settlement of the foundation. However, the above calculation method is highly dependent on the measured data and cannot reflect the distribution law of creep settlement. And many calculation parameters lack practical physical meaning. Therefore, it is necessary to select the appropriate constitutive model considering the creep effect of soil to calculate creep settlement.

Yao et al. (2009) proposed the experimental law of friction, compression and dilatancy of over-consolidated soil. On the basis of the modified Cambridge model, a unified hardening parameter that can uniformly describe the shear-shrinkage, shear-strain, strain hardening and strain softening of over-consolidated soil is proposed. The UH model was established by introducing this parameter into the law of yield surface hardening. This model only adds a soil parameter to the modified Cambridge model, which can reasonably describe the overconsolidation characteristics of the soil and has good computational stability.

In this paper, the UH model considering the time effect is used as the constitutive model of the subgrade soil to calculate the creep deformation of the soil. The model follows the yield surface equation and the flow law of the UH model. Based on the “timeline” theory of Bjerrum (1967) the instantaneous normal compression line is selected as a reference line for calculating the creep time and overconsolidation parameter and the one-to-one correspondence between the time and the overconsolidation parameter is established. Further, the relationship between creep time and over-consolidation degree is clarified, so that the rheological problem of soil is transformed into the over-consolidation problem, which can better reflect the development law of deformation with time. Therefore, the rheological problem of soil is transformed into the problem of overconsolidation, which can better reflect the development law of deformation with time. The constitutive equation of the model is

\[
\begin{bmatrix}
\frac{dp}{dt} + B_d dt \\
\frac{dq}{dt} + B_s dt
\end{bmatrix} =
\begin{bmatrix}
K \cdot A_1 & 3KG \cdot A_2 \\
3KG \cdot A_2 & 3G \cdot A_3
\end{bmatrix}
\begin{bmatrix}
d\varepsilon_v \\
d\varepsilon_s
\end{bmatrix}
\]

(1)

In the above formula, \(dp\) is the average normal stress increment, \(dq\) is the generalized shear stress increment, \(dt\) is the time increment, \(d\varepsilon_v\) is the total volume...
strain increment, $d\varepsilon_d$ is the total shear strain increment, $K$ is the elastic bulk modulus, and $G$ is Elastic shear modulus. $A_1$, $A_2$, $A_3$, $B_1$ and $B_2$ can be determined by the relevant soil parameters.

As shown in Table 1, when using this model to predict the creep deformation of soil, the required parameters are soil parameters with practical physical meaning, and the calculation results have high reliability.

| Parameter | Physical meaning |
|-----------|------------------|
| $\lambda$ | Slope of normal compression line in e-lnp plane |
| $\kappa$ | Slope of elastic springback line in e-lnp plane |
| $M$ | Critical state stress ratio |
| $\mu$ | Poisson's ratio |
| $N$ | Pre-consolidation pressure |
| $c_\alpha$ | Secondary consolidation coefficient |

### 4 FINITE ELEMENT MODEL

The finite element software ABAQUS, which can be used for the secondary development of material constitutive relations based on the UH model considering time effect, is used to calculate the long-term creep settlement of natural subgrade soil under high-speed railway. After symmetry simplification, the model established by ABAQUS software is shown in Figure 3. The foundation depth is 70m, the width is 50m, and the longitudinal thickness is 0.95m. The pile length of the CFG pile is 20m, the pile diameter is 0.4m, the plane distribution is square, the pile spacing is 1.5m, and 15 piles are arranged along the transverse direction. The concrete slab is 50m long, 0.95m wide and 0.25m thick. The ballastless track plate is 2.6m wide and 0.2m thick; the support layer is 3.8m wide and 0.3m thick. The embankment is 3.5m high and the slope of the slope is 1:1.5. The surface layer of the bed is 0.4m thick, the bottom of the bed is 2.3m thick, and the embankment under the bed is 0.8m thick. The hexahedral mesh property is selected, and the structural division method is adopted. The pile is laid on four sides along the semicircular edge, and 50 species are arranged along the length direction. The remaining parts are all arranged in a global manner. Among them, the ground and the pile contact parts are arranged in four kinds along the semicircular side, and 50 kinds are arranged in the depth direction. All units use the C3D8 element type (eight-node linear hexahedral element) in a three-dimensional stress state.

![Fig. 3. Finite element model mesh.](image)

The foundation soil constitutive model adopt the UH model considering time effect. The model parameters are determined based on the natural roadbed soil under a section of high-speed railway near Qufu East Station. Subgrade materials often use compacted bulk packing, so its constitutive model used a molar coulomb model that considers elastoplasticity. Both the CFG pile and the ballastless track adopt an elastic model. The values of the relevant model parameters are shown in the table below.

| Parameters | Value | Parameters | Value |
|------------|-------|------------|-------|
| $\lambda$  | 0.047 | $N$        | 0.68  |
| $\kappa$   | 0.0094| $c_\alpha$ | 0.00326|
| $M$        | 1.2   | $e$        | 0.85  |
| $\mu$      | 0.3   | Severe     | 20    |

| Part name | Severe (KN·m⁻¹) | Elastic Modulus (MPa) | Poisson's ratio | Internal friction angle | Cohesion (KPa) |
|-----------|-----------------|-----------------------|----------------|------------------------|---------------|
| Subgrade  | 22 30           | 0.25 47.1 9.82       |                |                        |               |
| Pile      | 25 1200        | 0.20 - -              |                |                        |               |
| Board     | 24 30000       | 0.20 - -              |                |                        |               |
| Rail      | 24 30000       | 0.16 - -              |                |                        |               |
5 CALCULATION RESULTS AND ANALYSIS

Figure 4 and 5 are the vertical displacement cloud maps before and after the creep, respectively. The model is a symmetric simplified model, so the cloud map also has the same symmetry. According to the following figure, the vertical displacement distribution of foundation is small on both sides and large in the middle. The lateral distribution of foundation settlement deformation under the subgrade of high-speed railway is relatively gentle, which is conducive to the smoothness of the horizontal direction of high-speed railway track.

Figure 6 and 7 show the vertical displacement cloud diagram of the pile before and after the creep, respectively. It is not difficult to find that the settlement law of the pile is small on both sides and large in the middle, and the peak of settlement deformation is distributed at the top position of the pile. This is because the pile has a certain elasticity and compressibility. As the depth of the foundation increases, the frictional resistance of the pile increases, that reduces the compressing deformation of the pile.

Figure 8 is a creep settlement curve of various points along the width direction of the foundation surface, and the three curves represent the creep settlement values in the first, third and fifth years respectively. Analysis of the following graph shows that the creep settlement is distributed in a concave curve. The maximum values of settlement are distributed at the center of the foundation, and the minimum values of settlement are distributed away from the two sides of the high-speed railway. At the three time points, the settlement values of the center point of the foundation under the subgrade are about 2.80mm, 3.75mm and 4.20mm respectively, and the settlement values at the foot of the subgrade are about 2.59mm, 3.53mm and 3.99mm respectively, with a difference of 0.21mm, 0.22mm and 0.21mm. This shows that the smoothness of the horizontal direction of the high-speed railway is fully guaranteed.
In Figure 9, points A to C are calculated nodes which are equidistant from the surface of the foundation. Figure 10 shows the creep settling curves of the above three nodes over time in 5 years. It can be found from the analysis of this curve that the creep settlement of every node on the surface of the foundation grows faster at the beginning. However, with the development of time, the creep settlement curve gradually flattens, and the creep settlement grows more and more slowly. In addition, Table 4 shows the creep settlement values of each node at three time points. It is not difficult to find that the final creep settlement values of each node are all within the range of 3.90mm-4.23mm, and the settlement distribution is relatively uniform.

### Table 4. Comparison of settlement values of each node.

| The name of nodes | Settlement of 1 year(mm) | Settlement of 3 years(mm) | Settlement of 5 years(mm) |
|-------------------|--------------------------|--------------------------|--------------------------|
| A                 | 2.7245                   | 3.7329                   | 4.2271                   |
| B                 | 2.6421                   | 3.6058                   | 4.0804                   |
| C                 | 2.5481                   | 3.4689                   | 3.9178                   |

### 6 CONCLUSIONS

This paper introduced the UH model considering time effect and its main parameters for predicting creep. Using the secondary development of ABAQUS software, finite element modeling and calculation analysis were carried out. The main conclusions are as follows:

1. In the finite element analysis, the creep settlement distribution of the foundation under high-speed railway is small on both sides and large in the middle. The peak value of settlement deformation of CFG pile is distributed at the top of the pile.
2. The creep settlement is distributed in a concave curve along the width direction of the surface of the foundation. In addition, the maximum value of settlement is distributed near the center of the foundation. With the development of time, the creep settlement curve of the foundation gradually becomes gentle, and the creep settlement value increases more and more slowly.

### ACKNOWLEDGEMENTS

This paper is supported by the National Natural Science Foundation of China (Grant No. U1834206) and the Science and Technology Research and Development Plan of China Railway Corporation (Grant No. 2017G002 - W).

### REFERENCES

1) Sun, J. (1999): Rheological behavior and engineering application of geotechnical materials. *Construction Engineering Press*. (in Chinese)
2) Bishop, A. W., Lovenbury, H. T. (1969): Creep
characteristics of two undisturbed clays. *Proceedings of 7th International Conference of Soil Mechanics and Foundation Engineering*, 29-37.

3) Tavenas, F., Leroueil S., Rochelle P. L., et al. (1978): Creep behavior of an undisturbed lightly over consolidated clay. *Canadian Geotechnical Journal*, 15(3), 402-423.

4) Wang, Z. C., Qiao, L. P. (2011): A review and discussion on creep behavior of soil and its models. *Rock and Soil Mechanics*, 32(8), 2251-2259. (in Chinese)

5) Oliveira, P. I. V, Correia. A. A. S, Mira. E. S. P. (2013): Mitigation of creep deformations by preloading: laboratory study. *Proceedings of the Institution of Civil Engineers Geotechnical Engineering*, 166(6), 594-600.

6) Yin, J. H., Feng, W. Q. (2019): New simplified method for calculating consolidation settlement of clayey soils exhibiting creep and its verification. *Chinese Journal of Geotechnical Engineering*, 41(2), 5-8.

7) Yao, Y. P, Hou, W., Zhou, A. N. (2009): UH model: three-dimensional unified hardening model for overconsolidated clays, *Geotechnique*, 59(5), 451-469.

8) Kong, L. M., Luo, T., Yao, Y. P. (2015): Description of critical state for rate-dependent constitutive models. *Rock and Soil Mechanics*, 36(9), 2442-2450.

9) Sun, H. Y., Wang, Q. L. (2010): Accuracy Comparison Between Hyperbola Method and Exponential Curve to Validate Soft Foundation Settlement. *Coal Technology*, 29(1), 167-170. (in Chinese)

10) Ma, S. C., Hu, J. X., Ma, Y. Y. (2014): On Prediction Method and Accuracy of Post-Construction Settlement for the Substructure of the High-Speed Rail. *Natural Science Journal of Xiangtan University*, 29(1), 38-44. (in Chinese)

11) Bjerrum, L. (1967): Engineering geology of norwegian normally consolidated marine clays as related to the settlements of buildings. *Geotechnique*, 17(2), 83-119.