Jordan Journal of Civil Engineering, Volume **14**, No. **1**, **2020**

Analysis of Lacustrine Facies Soft Soil Roadbed Settlement Based on a Viscoelastic-Plastic Model

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ABSTRACT

Soft soil deformation is not only related to the stress state, but is also related to time and exhibits viscoelastic–plastic characteristics. The generalized Nishihara model was developed from 1D state into 3D state and the viscoplastic soft matrix based on the Drucker–Prager yield model and the viscoelastic soft matrix of 2D and 3D units were established using the incremental finite element method. On the basis of the aforementioned model and matrices, a program for the soft soil adhesion elastoplastic constitutive model was developed using ADINA software. Lastly, the program was used to calculate the soft clay roadbed settlement of Dongting Lake and the settlement change law of the embankment centerline on the 300th day was determined. Results are consistent with the measured values, indicating that the secondary development of this research can be used to analyze the engineering problems of lacustrine facies soft soil roadbed settlement.

KEYWORDS: Lacustrine facies soft soil, Analysis of subsidence, Viscoelastic–plastic model, Generalized Nishihara model, Secondary development, Plane strain problem.

INTRODUCTION

The economy zoo that surrounds lakes has gradually formed with the rapid development of the inland economy in China and building on the lacustrine facies soft foundation of intercity roads has become increasingly common. The settlement and uneven settlement of soft foundation must be strictly controlled to ensure road safety and normal operation. Therefore, soft soil roadbed settlement is a key issue in design and construction. The analysis of soft soil roadbed settlement has elicited considerable attention among local and foreign scholars (Loganathan et al., 1993; Liu Song-Yu and Jing Fei, 2003; Curtis et al., 2009; Jiang Min et al., 2010; Hu Sheng-Xia et al., 2014; Wei Li-Min et al., 2010). Loganathan (1993) studied soft ground settlement data and proposed a deformation analysis method. Using the Cambridge model for simulation, the author found two methods to obtain a consistent vertical subsidence trend. Liu Song-Yu and Jing Fei (2003) developed an embankment settlement prediction method for soft soil subgrade construction in phases based on the Asaoka observation method; they then applied the method to Jiang sub-marine soft foundation and performed settlement prediction analysis. Curtis et al. (2009) proposed a viscoelastic–plastic model that involves the plane strain analysis of embankment

Received on 27/9/2019.
Accepted for Publication on 5/2/2020.

settlement deformation and obtained sedimentation simulation values that are close to the measured values. Jiang Min et al. (2010) simulated a seawall project on marine soft foundation based on the improved cam-clay model and found that the model can accurately reflect the seawall below a large area of the factory backfill foundation settlement and lateral deformation. Meanwhile, it can be well considered in the process of filling the super static pore water pressure at different depths of foundation accumulation and dissipation process. Sheng- Xia Hu et al. (2014) proposed weakening the stress path of change of an elastic–viscoplastic model to represent the stress–strain relationship of soft clay. They adopted the finite element method to calculate the settlement of soil under preloading and verified the proposed method through a concrete example. Li-Min Wei et al. (2010) established a soft soil large stick strain elastic–plastic finite element analysis method, developed the corresponding finite element program and verified the reliability of the program through field measurement. These previous studies have focused on soft foundation settlement calculation and forecast of theoretical research. However, the layered summation method is still mostly adopted in engineering applications to calculate the settlement of soft foundation. Abdullah (2011) pointed out that for any type of geotechnical problem where no exact solution is available, the elasto/viscoplastic finite element approach may be used to obtain a high-precision solution. In our current specification (JIG D30-2004, 2004) of soft foundation settlement calculation, the primary consolidation settlement stratified summation method is adopted and total settlement based on primary consolidation settlement is determined through empirical coefficient modification. This method can satisfy the requirements of engineering practice to a certain extent. However, the calculation of post-construction settlement of soft ground requirement exhibits low accuracy.

In the current work, the 1D generalized Nishihara model (Yin Guang-Zhi, 2008) is extended to the viscoelastic–plastic model of the 3D stress state on the basis of the analysis of the rheological properties of soft soil. Then, the viscoelastic–plastic model for solving the plane problem is added to the ADINA finite element program for the settlement analysis of soft clay subgrade in the Dongting Lake area. The calculated and measured values of the settlement are compared and analyzed to verify the generalized viscoelastic–plastic model for analyzing the accuracy and reliability of practical engineering problems in soft foundation settlement.

Rheological Properties of Soft Clay Foundation

Water and gas in the pores of the subgrade are partially extruded under an external load and soil particles are rearranged to deform the soil skeleton. On the one hand, the discharge of pore fluid is hindered due to friction between the soil particles and the pore fluid and soiled formation is delayed. Contact between soil particles is combined with contact between water membranes. The viscosity of combined water must also undergo a process for soil deformation. Therefore, the settlement of a roadbed is not only related to stress, but also to time (i.e., rheological properties).

The rheological property of any soil type is absolute and its remarkable degree is closely related to the microstructure of soil. Soft clay has a lamellar structure and frequently exhibits notable rheological properties (Dan Han-Bo, 2009). The rheological properties of soil primarily include creep, stress relaxation, long-term strength and elastic aftereffect. The settlement of soft soil subgrade under a long-term external load can be attributed to the creep problem of soil. Sheahan (1995) indicated that the typical creep process of soil under a triaxial condition can be divided into three stages: creep transition, stable creep and accelerated creep; the corresponding creep rates are attenuation, constant increase and gradual increase with time. Although many soil rheological models are available, classical rheological models are basically divided into two types: viscoelastic and viscoelastic–plastic models. Classical rheological model theory exhibits the advantage of providing clear physical concepts; thus, the two types of models are frequently used in studying the rheological properties of soil at present. The rheological properties of a saturated soft clay roadbed are mostly related to deformation time and stress level, showing neither an elastomer nor a plastic body, but a viscoelastic–plastic body with viscous, elastic and plastic properties (Qian Jia-Huan, 1998). Therefore, the viscoelastic–plastic model should be adopted.

3D Viscoelastic–Plastic Rheological Model

3D Generalized Nishihara Model

In rheological mechanics, various rheological basic elements are typically combined to develop a more complex model that can describe the rheological properties of geotechnical materials. For example, the generalized Nishihara model has many applications and is relatively complete. It can describe the attenuating and stable creep stages and can provide results that are consistent with the experimental results of geotechnical materials (Pan Xiao-Ming et al., 2010; Fu Gui-Hai et al., 2013). The 1D generalized Nishihara model is composed of a Hooker body, two Kelvin bodies and a series of Bingham bodies. When $\sigma_0 < \sigma_s$, the model degenerates into a generalized Kelvin model.

$$\varepsilon(t) = \frac{\sigma_0}{E_0} + \frac{\sigma_0}{E_1}(1 - e^{-E_1 t/\eta_1}) + \frac{\sigma_0}{E_2}(1 - e^{-E_2 t/\eta_2}) \quad (1)$$

When , $\sigma_0 \geq \sigma_s$

$$\varepsilon(t) = \frac{\sigma_0}{E_0} + \frac{\sigma_0}{E_1}(1 - e^{-E_1 t/\eta_1}) + \frac{\sigma_0}{E_2}(1 - e^{-E_2 t/\eta_2}) + \frac{(\sigma_0 - \sigma_s)t}{\eta_3}, \quad (2)$$

where E_0 is the elastic modulus of the Hooker body; E_1 and E_2 are the elastic moduli of the generalized Kelvin body spring elements; η_1, η_2 and η_3 are the viscous coefficients of the generalized Kelvin body and the Bingham body viscous pot element; σ_s is the yield stress of the Bingham body plastic element; σ_0 is the stress at both ends of the model; and t is the time.

Soil samples are typically in a 3D stress state under actual conditions. If the creep calculation formulae; i.e., Equations (1) and (2), are used in 1D stress state, then soil strain is not strict. A rheological model is difficult to express with visualized physical components in a multi-dimensional state, but a rheological equation can be directly derived from the 1D model to the 3D model, provided that the corresponding symbol is used. The following pair of adjustments is made (Sun Jun, 1999):

$$\sigma \leftrightarrow s_{ij}, \varepsilon \leftrightarrow e_{ij}, E \leftrightarrow 2G, \eta \leftrightarrow 2H \quad (3)$$

By transforming Equation (3) in accordance with Equations (1) and (2), the constitutive equation of the generalized Nishihara creep model in 3D state can be directly written as follows:

$$\{\varepsilon_{ij}\} = \left[\frac{1}{2G_H} + \frac{1}{2G_1}(1 - \exp(-\frac{G_1 t}{H_1}) + \frac{1}{2G_2}(1 - \exp(-\frac{G_2 t}{H_2})\right]\{\sigma_{ij}\} + \left\langle \frac{F}{F_0} \right\rangle \frac{t}{2H_3} \frac{\partial \theta}{\partial \{\sigma_{ij}\}} \quad (4)$$

where G is the shear modulus that reflects the change inelastic properties caused by biased stress under 3D stress; i.e., $G_H = \frac{E_0}{2(1+\mu)}$, $G_1 = \frac{E_1}{2(1+\mu)}$ and $G_2 = \frac{E_2}{2(1+\mu)}$; H_1 and H_2 are viscoelastic viscosity coefficients and H_3 is viscoplastic viscosity coefficient.

Viscoelastic Unit Flexibility Matrix

In accordance with classical rheological mechanics theory, the total strain $\{\varepsilon_{ij}\}$ in a nonlinear continuum medium consists of viscoelastic strain $\{\varepsilon_{ij}^{ve}\}$ and viscoplastic strain$\{\varepsilon_{ij}^{vp}\}$ components. The former includes instantaneous elastic strain and viscoelastic creep. Thus, the total strain can be expressed as follows:

$$\{\varepsilon_{ij}\} = \{\varepsilon_{ij}^{ve}\} + \{\varepsilon_{ij}^{vp}\} \quad (5)$$

The viscoelastic strain expression can be derived from Equation (4) as:

$$\{\varepsilon_{ij}^{ve}\} = \left[\frac{1}{2G_H} + \frac{1}{2G_1}(1 - \exp(-\frac{G_1 t}{H_1})) + \frac{1}{2G_2}(1 - \exp(-\frac{G_2 t}{H_2}))\right]\{\sigma_{ij}\} \quad (6)$$

The viscoelastic properties of soft soil can be regarded as instantaneous elasticity in numerical calculation. For plane problems, the viscoelastic flexibility matrix $[C]^{ve}$ of soft soil can be expressed using the following formula with reference to the generalized Hooke's law:

$$[C]^{ve}=\frac{1}{G_t}\begin{bmatrix}1 & -\mu & 0 & -\mu\\ -\mu & 1 & 0 & -\mu\\ 0 & 0 & -2(1+\mu) & 0\\ -\mu & -\mu & 0 & 1\end{bmatrix}, \quad (7)$$

where G_t is the equivalent viscoelastic modulus that is the sum of the instantaneous elastic modulus and the viscoelastic modulus. In accordance with the principle of elastic–plastic mechanics, the equivalent viscoelastic modulus of soft soil can be obtained using Equation (6) as follows:

$$G_t=\frac{1}{\frac{1}{2G_H}+\frac{1}{2G_1}(1-\exp(-\frac{G_1 t}{H_1}))+\frac{1}{2G_2}(1-\exp(-\frac{G_2 t}{H_2}))} \quad (8)$$

Viscoplastic Unit Flexibility Matrix

The viscoplastic strain expression can also be derived using Equation (4) as follows:

$$\{\varepsilon_{ij}^{vp}\}=\left\langle\frac{F}{F_0}\right\rangle\frac{t}{2H_3}\frac{\partial\theta}{\partial\{\sigma_{ij}\}} \quad (9)$$

where $\left\langle\frac{F}{F_0}\right\rangle$ is a switching function, $\left\langle\frac{F}{F_0}\right\rangle=\begin{cases}\frac{F}{F_0} & (F>0)\\ 0 & (F<0)\end{cases}$; F_0 is an arbitrary value used to make the coefficient dimensionless, typically $F_0=1$; θ is the plastic potential; and F is the yield function, assuming that soft soil follows the Drucker–Prager (DP) yield criterion. The associated flow rule is adopted.

For the DP yield function F,

$$Q=F=\frac{6\sin\varphi}{3-\sin\varphi}\sigma_m+\sqrt{3J_2}-\frac{6c\bullet\cos\varphi}{3-\sin\varphi} \quad . \quad (10)$$

Its incremental constitutive relationship can be expressed as:

$$C_1=\frac{6\sin\varphi}{3-\sin\varphi},\ C_2=\sqrt{3},\ \ C_3=0\ ,$$

where σ_m is the average stress; J_2 is the second invariant of the stress deviation; and c and φ are the cohesive force and internal friction angle of soft soil, respectively.

When $F>0$,

$$\left\langle\frac{F}{F_0}\right\rangle\frac{\partial\theta}{\partial\{\sigma_{ij}\}}=F(\frac{6\sin\varphi}{3-\sin\varphi}\frac{[P]}{3\sigma_m}+\frac{\sqrt{3}}{2}\frac{[Q]}{\sqrt{J_2}})\{\sigma_{ij}\}\ , \quad (11)$$

where [P]and [Q] are the coefficient matrices.

For plane problems, [P] and [Q] are presented as follows:

$$[p]=\frac{1}{3}\begin{bmatrix}1 & 1 & 0 & 1\\ 1 & 1 & 0 & 1\\ 0 & 0 & 0 & 0\\ 1 & 1 & 0 & 1\end{bmatrix} \quad \text{and} \quad [Q]=\frac{1}{3}\begin{bmatrix}2 & -1 & 0 & -1\\ -1 & 2 & 0 & -1\\ 0 & 0 & 6 & 0\\ -1 & -1 & 0 & 2\end{bmatrix}$$

For the increment of linear viscoplastic creep strain, the following equation can be used:

$$\Delta\varepsilon^{vp}=\dot{\varepsilon}^{vp}\,\Delta\mathbf{t} \quad . \quad (12)$$

From Equation (9), the following formula can be derived:

$$\dot{\varepsilon}^{vp}=\left\langle\frac{F}{F_0}\right\rangle\frac{1}{2H_3}\frac{\partial\theta}{\partial\{\sigma_{ij}\}} \quad . \quad (13)$$

The increment of viscoplastic strain with time can be obtained by substituting Equation (13) into Equation (12):

$$\Delta\varepsilon^{vp}=\left\langle\frac{F}{F_0}\right\rangle\frac{\Delta t}{2H_3}\frac{\partial\theta}{\partial\{\sigma_{ij}\}} \quad . \quad (14)$$

Suppose $a_1=\frac{2\sin\varphi}{(3-\sin\varphi)\sigma_m}F$ and $a_2=\frac{\sqrt{3}}{2\sqrt{J_2}}F$. Then, the viscoplastic flexibility matrix of soft soil is deduced as follows:

$$[C]^{vp} = \frac{1}{3}\begin{bmatrix} a_1 + 2a_2 & a_1 - a_2 & 0 & a_1 - a_2 \\ a_1 - a_2 & a_1 + 2a_2 & 0 & a_1 - a_2 \\ 0 & 0 & 6a_2 & 0 \\ a_1 - a_2 & a_1 - a_2 & 0 & a_1 + 2a_2 \end{bmatrix}. \qquad (15)$$

Equations (7) and (15) are the flexibility matrices of the generalized Nishihara model for numerical calculations. They must be connected to the nonlinear finite element program ADINA for numerical calculation. ADINA adopts the object-oriented language standard FORTRAN for secondary development and the constitutive model is provided to the user in the form of a dynamic link library (DLL) file. During calculation, the main program will automatically direct the user to the DLL file of the constitutive model that he/she has specified. For the user-defined constitutive model, the DLL file is automatically generated in the Compaq Visual Fortran 6.6A development environment through the Make file tool provided by ADINA to connect the modified *.f files.

The secondary development steps of the ADINA soft soil constitutive model are as follows.

(1) The subroutine included in the ADINA installation directory is modified in accordance with the flexibility matrix of Equations (7) and 15). The meaning of the included parameters is provided in ovl40u_vp1.f; thus, this subroutine is selected for modification. The ovl40u_vp1.f subroutine is compiled with the Compaq Visual Fortran 6.6A program and the corresponding obj file is generated. Lastly, the generated obj file is copied into the ADINA installation directory (C:\Program Files\ ADINA \ ADINA System 8. 42\ usrdll).

(2) The "Run" button in the start menu is clicked, and "cmd" is entered to start the DOS system.

(3) The Fortran environment is set up: cd C:\Program Files\Microsoft Visual Studio\DF98\BIN\dfvars.

(4) The following are compiled: cd C:\Program Files\ ADINA\ADINA System 8.42\ usrdll C:\Program Files\ ADINA\ADINA System 8.42\usrdllnmake /f makefile.adusr

(5) If the compilation is successful, then a new adus.dll file is generated in the usrdll folder. The original dll file in the bin folder of ADINA is backed up and the newly generated adusr.dll file is copied into the bin folder.

(6) The input parameters are set in the ADINA User Interface in accordance with the variables in the subroutine for calculation.

Test Verification of the Soft Clay Viscoelastic Model

Triaxial Creep Test of Soft Soil

At present, a strain-controlled triaxial apparatus is used in most laboratories. A creep test requires the relationship between strain and time to be observed under constant stress. Therefore, a strain-controlled triaxial apparatus is unsuitable for a creep test. The instrument used in the current test is based on a TSZ-60A fully automatic triaxial apparatus that is modified into a transverse beam compression system to maintain a constant force in the axial direction. An electronic percentile meter is installed on the compression bar to measure deformation in soil samples. The modified triaxial creep equipment is shown in Fig. 1. The tested soil sample is processed with a diameter of 39.1 mm and a height of 80 mm. The sample, which is collected from atypical soft soil section in the Dongting Lake area, belongs to lacustrine depositional soft soil. This soil type exhibits the typical characteristics of a large void ratio, high water content, low shear strength and high compressibility. The modified triaxial creep equipment is used to perform undrained creep tests under different confining pressures: 50, 100, 150 and 200kPa. The creep curve of soft soil under a confining pressure is presented in Fig. 2. As shown in the figure, soft soil in the Dongting Lake area exhibits evident nonlinear creep characteristics. These characteristics gradually manifest with an increase in deviator stress level. Accelerated creep appears until failure occurs under high deviator stress.

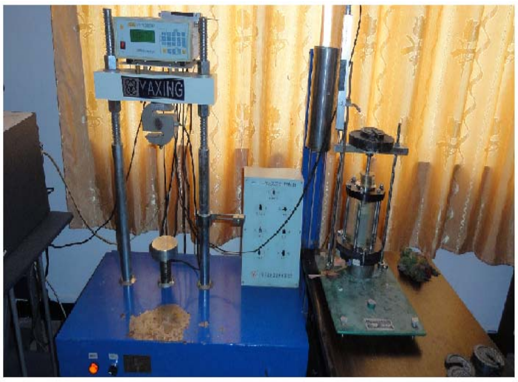


Figure (1): Modified triaxial creep equipment

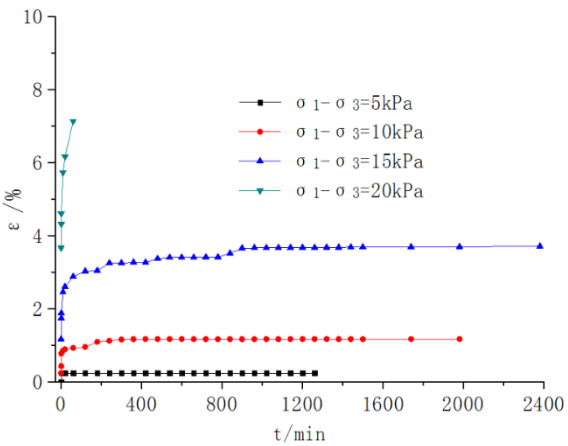


Figure (2): Creep curves of soft clay under 100 kPa confining pressure

Data Fitting and Parameter Determination

To fit the parameters conveniently into the experimental data, the expressions of the axial strain of the viscoelastic–plastic model of the generalized Nishihara model in3D stress state can be obtained from (Jiang Min e al. (2010) and Wei Li-Min et al. (2010):

$$\varepsilon_{11(t)} = \frac{\sigma_\Pi}{9K} + \frac{\sigma_T}{3G_H} + \frac{\sigma_T}{3G_1}[1-\exp(-\frac{G_1 t}{H_1})] + \frac{\sigma_T}{3G_2}[1-\exp(-\frac{G_2 t}{H_2})] + [\frac{2\sin\varphi}{3(3-\sin\varphi)} + \frac{\sqrt{3}\sigma_T}{2\sqrt{J_2}}]t \ , \qquad (16)$$

where $\sigma_T = \sigma_1 - \sigma_3$, $\sigma_\Pi = \sigma_1 + \sigma_2 + \sigma_3 = \sigma_1 + 2\sigma_3$ (for the triaxial rheological tests, $\sigma_2 = \sigma_3$),

$$K = \frac{E_0}{3(1-2\mu)} ,$$

$$J_2 = \frac{1}{6}[(\sigma_1-\sigma_2)^2 + (\sigma_1-\sigma_3)^2 + (\sigma_2-\sigma_3)^2 .$$

Equation (16) has a complex form and numerous variables; thus, the following substitutions are performed to facilitate fitting operation:

$$\left.\begin{array}{l} p_1 = \dfrac{\sigma_\Pi}{9K} + \dfrac{\sigma_T}{3G_H} ....p_2 = \dfrac{\sigma_T}{3G_1} \\ p_3 = \dfrac{G_1}{H_1} ....p_4 = \dfrac{\sigma_T}{3G_2} \\ p_5 = \dfrac{G_2}{H_2} ....p_6 = \dfrac{1}{2H_3}\left\langle \dfrac{F}{F_0} \right\rangle (\dfrac{2\sin\varphi}{3(3-\sin\varphi)} + \dfrac{\sqrt{3}\sigma_T}{2\sqrt{J_2}}) \end{array}\right\} . \ (17)$$

Equation (18) can be obtained by substituting Equation (17) into Equation (16).

$$\varepsilon_{11(t)} = p_1 + p_2(1-e^{-p_3 t}) + p_4(1-e^{-p_5 t}) + p_6 t \quad (18)$$

The results of the triaxial rheological test can be fitted using Origin software to define the fitting function in accordance with Equation (19). Subsequently, parameters p_1 , p_2 , p_3 , p_4 , p_5 and p_6 can be obtained. The fitting curves of the 100 kPa confining pressure and different biases are shown in Fig. 3. The fitting correlation coefficients are 0.98042 and 0.98513, indicating that the fitting curves are consistent with the experimental data.

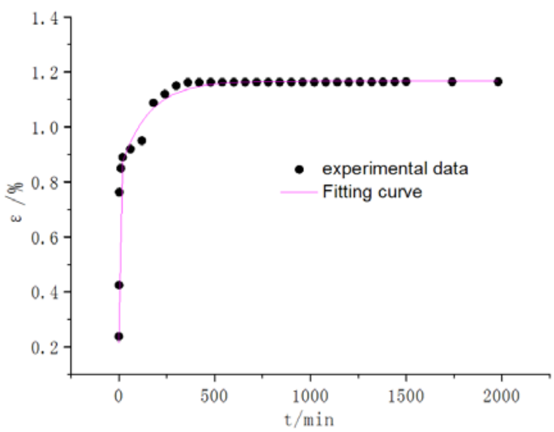
The physical parameters of the generalized Nishihara model can be obtained by inverting Equation (17).

$$\left.\begin{array}{l} G_H = \dfrac{(1-2\mu)\sigma_\Pi + 2(1+2\mu)\sigma_T}{6p_1(1+\mu)} ....G_1 = \dfrac{\sigma_T}{3p_2} \\ H_1 = \dfrac{G_1}{p_3} ....G_2 = \dfrac{\sigma_T}{3p_4} \\ H_2 = \dfrac{G_2}{p_5} ....H_3 = \dfrac{1}{2p_6}\left\langle \dfrac{F}{F_0} \right\rangle (\dfrac{2\sin\varphi}{3(3-\sin\varphi)} + \dfrac{\sqrt{3}\sigma_T}{2\sqrt{J_2}}) \end{array}\right\} (19)$$

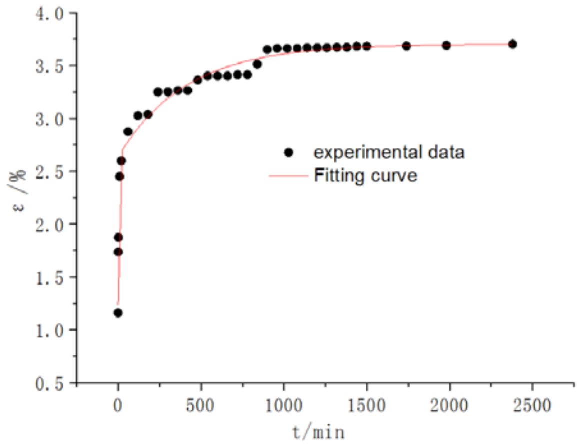
The test data of the soil samples at the site indicate that $c = 7.44\text{kPa}$, $\varphi = 4.57^0$ and $\mu = 0.38$ can be selected. The physical parameters of the generalized Nishihara model can be obtained by combining p_1, p_2 and p_3, as shown in Table 1.

Table 1. Parameters of the viscoelastic–plastic model of soft clay

Confining pressure/ deviatoric stress	G_H (MPa)	G_1 (MPa)	G_2 (MPa)	H_1 (d.MPa)	H_2 (d.MPa)	H_3 (d.MPa)
0.1 MPa/0.01 MPa	6.32	31.46	85.64	15.63	230.23	420.32
0.1 MPa/0.015MPa	5.63	26.58	70.36	15.98	260.62	530.72



(a) When bias pressure is 10 kPa



(b) When bias pressure is 15 kPa

Figure (3): Fitting curves of soft clay under 100 kPa confining pressure

Numerical Simulation of the Creep of Soft Soil

A cylinder with a diameter of 39.1 mm and a height of 80 mm is prepared in accordance with the stress state of the triaxial creep and shear of soft soil. The vertical displacement is restrained at the bottom, confining pressure is applied to the side of the cylinder and axial pressure is applied to the top of the cylinder. In this work, the creep behavior of soft soil under a 100 kPa confining pressure and different deviating stresses (e.g., 10 kPa and 15 kPa) is simulated as an example. The finite element model of the triaxial simulation test of soft soil is shown in Fig. 4. The calculation parameters of the viscoelastic–plastic constitutive model of soft soil are provided in Table 1. The results of the ADINA simulation are compared with the experimental values in Fig. 5. This figure shows that the simulation values are close to the experimental values, verifying the validity and correctness of the developed viscoelastic–plastic model for soft soil.

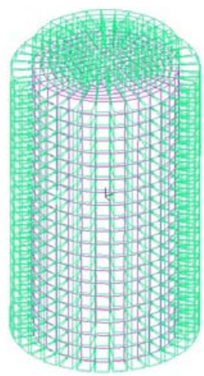


Figure (4): Finite element calculation model for the triaxial test

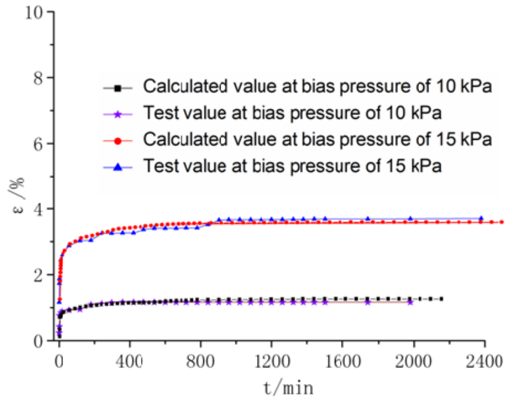


Figure (5): Comparison between experiment results and calculated values of soft clay under 100 kPa confining pressure

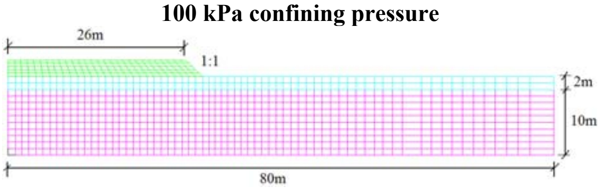


Figure (6): Finite element model of the low embankment

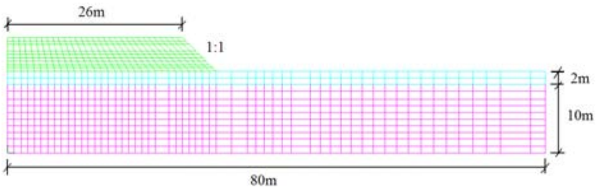


Figure (7): Finite element model of the high embankment

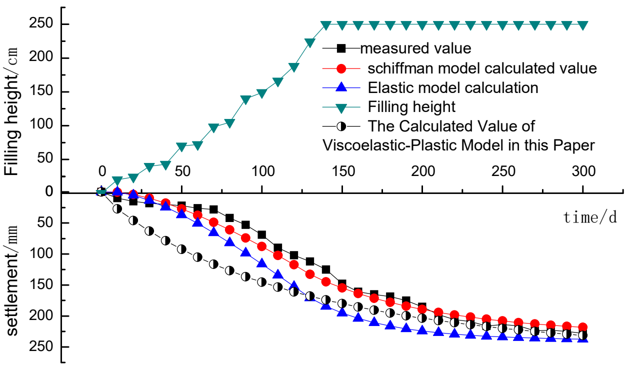


Figure (8): Settlement curves of the low embankment varying with time

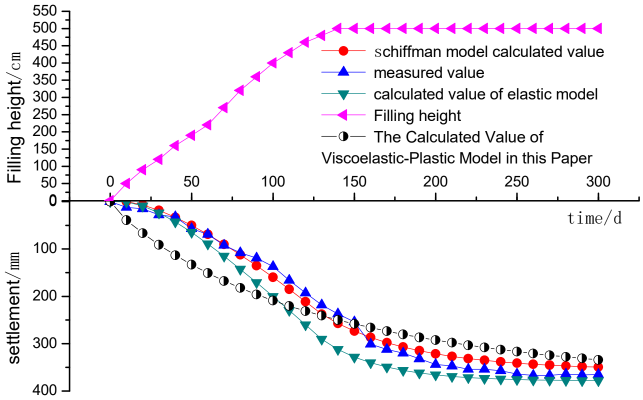


Figure (9): Settlement curves of the high embankment varying with time

Engineering Application of the Model

Engineering Survey

The Yueyang–Changde Highway is a part of the Hangzhou–Ruili Highway, which is the 12th horizontal section of the national expressway planning network and the first horizontal section of the Hunan Expressway planning network with five vertical and seven horizontal sections. The total length of the highway is 140.98 km and the length of the soft foundation treatment section is 62.89 km, accounting for approximately 45% of the total length. Yueyang–Changde is the first highway in China to cross the soft foundation of a lake area for a long distance. The soft soil distribution area along the highway is a typical lake soft soil deposition area. The soft soil is uneven and widely distributed, with a depth ranging from a few meters to several tens of meters. The soft soil of a lake area highly differs from the soft soil of marine and river beaches due to the particularity of sediments, compositional materials and stress history. To obtain an effective method suitable for the reinforcement of a lake's soft foundation, the test section of the soft foundation is set up before the construction of the highway and considered from the following aspects. First, the rationality of the construction drawing design is checked by observing settlement and displacement, including the accuracy of the design parameters and calculation results. Second, a complete set of construction technology, construction method and quality control measures is summarized by constructing a test road that can effectively guide the large-scale construction of the project.

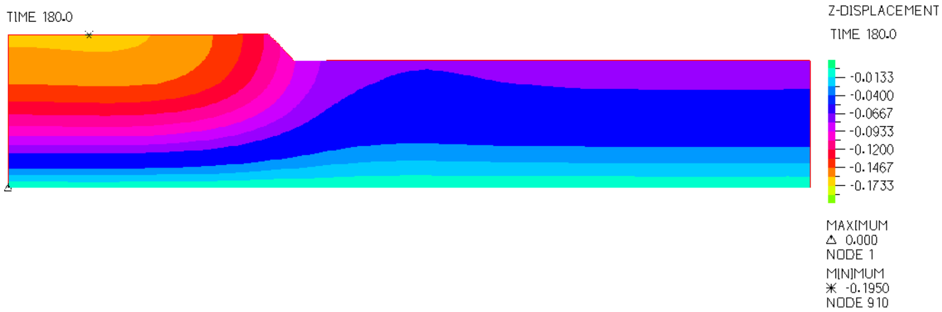
Considering these reasons, relevant test sections in Yueyang and Changde are selected for construction in accordance with the geological conditions of the Dongting Lake area and the opinions of the owners and the design and scientific research units. In this work, two areas of a test section; namely, the middle and low embankment (2.5 m filling height) and the high embankment (5.0 m filling height), are selected for research. Relevant field settlement observations are conducted on the test section to obtain test data.

Settlement Numerical Analysis of Soft Foundation

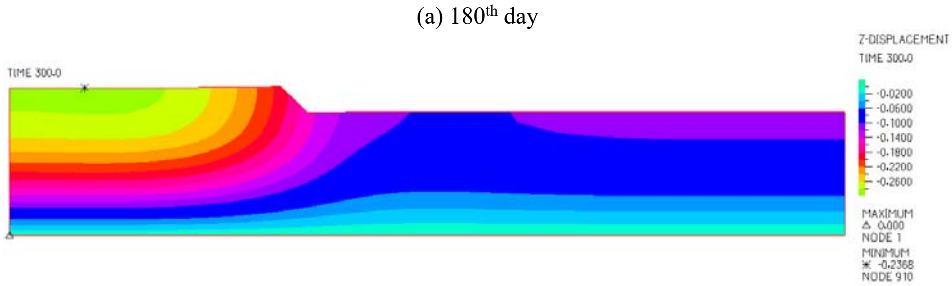
The problem can be regarded as symmetrical plane strain on the basis of the characteristics of the highway embankment. Thus, a half of the embankment is selected as the research object. The width of the model is set as 80 m to reduce the boundary effect. The life–death element is used to simulate the construction process on site and the embankment is filled in layers with 0.5 m per layer. In the simulation, a symmetrical boundary is used on the left side of the model, a horizontal displacement is constrained on the right side and vertical and horizontal displacements are constrained on the bottom boundary. The finite element models of the low and high embankments are shown in Figs. 6 and 7, respectively. The Mohr–Coulomb model is adopted for the silty clay of the embankment fill and the surface layer, and the generalized Nishihara model is used for the silty clay of silt. The calculation parameters of the finite element models are provided in Table 2.

Table 2. Calculation parameters of the finite element models

Soil layer	G_H (MPa)	G_1 (MPa)	G_2 (MPa)	H_1 (MPa·h)	H_2 (MPa·h)	H_3 (MPa·h)	γ (kN/m^3)	E_s (MPa)	C (kPa)	Φ (°)
Embankment fill	/	/	/	/	/	/	20.0	10	15	25
Silty clay	/	/	/	/	/	/	19.5	10	13	28
Muddy silty clay	5.6	26.6	70.4	0.6658	10.86	22.11	19.0	4.0	7.4	4.6

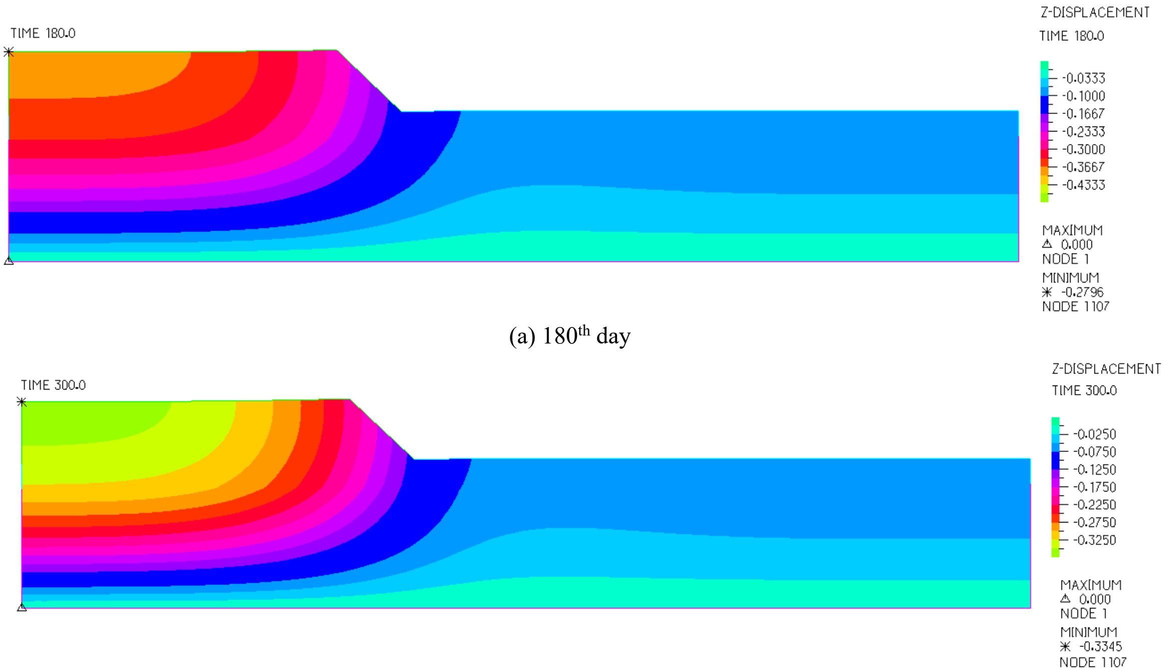


(a) 180th day



(b) 300th day

Figure (10): Settlement nephogram of the low embankment



(a) 180th day

(b) 300th day

Figure (11): Settlement nephogram of the high embankment

The numerical results of the viscoelastic–plastic model presented in this study (Deng Zong-Wei et al., 2014) are compared with those obtained using other methods (the Schiffman and elastic models are calculated under step loading), as shown in Figs. 8 and 9. Figs. 10 and 11 present the settlement nephograms of respectively the low and high fill embankments, for 180 days and 300 days. The analysis shows that the initial settlement of the viscoelastic–plastic model is larger than that of the measured and other calculated values. However, the calculated and measured values of the viscoelastic–plastic model gradually approach the other values over time. The differences between the calculated and measured values of the settlement of the low and high embankments are only 1.5% and 3.4%, respectively, on the 300th day. These values satisfy engineering requirements. Therefore, the finite element program developed in this study can be used to calculate the long-term settlement of a lake's soft foundation in practical engineering.

CONCLUSIONS

In this work, the viscoelastic and viscoplastic flexibility matrices of the generalized Nishihara viscoelastic–plastic model for the numerical calculation of plane problems are derived by using the DP yield criterion. After secondary development, the matrices are successfully added to the ADINA finite element method and the program is applied to the settlement analysis of the soft clay roadbed in the Dongting Lake area. The following main conclusions are drawn.

(1) Soft clay is a viscoelastic–plastic material. The 1D generalized Nishihara model can accurately present the deceleration and steady creep stages of soft clay and is consistent with the test results. The generalized 3D Nishihara model can more accurately and carefully describe the actual stress state of soil and the results obtained by applying the viscoelastic–plastic model to solve the rheological problems of soil are more realistic and reliable.

(2) Plane strain numerical analysis is performed on the settlement of the soft clay roadbed in the Dongting Lake area using the developed finite element program. The correctness of the rheological program based on the generalized Nishihara model is verified by comparing its results with the measured values. The program can be applied to the calculation of soft soil rheological problems and exhibits good engineering application values.

(3) The rheological model parameters determined by the curve fitting method can reflect the characteristics of soil samples in the most comprehensive manner and ensure the authenticity of the parameters used. This method is simple and accurate.

Acknowledgements: This study is financially supported by the China National Natural Science Foundation (Grant Numbers 51608183 and 51678226), the Natural Science Foundation of Hunan Province (Grant Number 2016JJ4013), the Hunan Science and the Hunan Provincial Department of Education Science Research Project Key Project (Grant Number 16A038). The authors greatly appreciate the helpful comments and suggestions of the anonymous reviewers.

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