IEREK PRESS Academic Research Community
http://www.press.ierek.com
ARChive
CrossMark
ISSN (Print: 2537-0154, online: 2537-0162)
International Journal on:
The Academic Research Community Publication
DOI: 10.21625/archive.v2i4.383

Research of One-Dimensional Consolidation of Clays Considering their Rehological Properties

Chen Zhuo[1], Deng JinGentgss[1], Yu Baohua[1], Weng Haoyang[1], Wang Jie[1], Yan Xinjiang[2]

[1] *China University of Petroleum(Beijing), Fuxue Road No.27, Changping District, Beijing, China*

[2] *CNOOC Research Institute, Sun Palace Street No.6, Chaoyang District, Beijing, China*

Abstract

The paper concerns the influence of time and strain-rate effects on the clays in one-dimensional consolidation under constant effective stress. An improved creep constitutive model is deduced, by analyzing the stress-strain theory developed by yin and sekiguchi. Treating the sample as a single system and applying the boundary conditions at the system level, differential mathematical equations to the consolidation problem of clays are obtained. The proposed differential mathematical equations have advantages in their ability to (i) not clarify the primary consolidation and secondary consolidation deformation. The error in calculating consolidation deformation which is caused by the argument about end of primary consolidation can be avoided. (ii) obtain the model parameters easily. How to achieve parameters by experiment is described in detail in the paper. (iii) be programmed and solved readily for the finite difference description of the problem. Results from clays have been used to examine the validity of the model. It is shown that the proposed model can describe the consolidation of clays well.

Keywords

consolidation; viscous; time; creep; strain rate.

1. Introduction

At present, the research on clay consolidation is mainly based on the consolidation theory of Terzaghi. After considering the mutual influence of pore pressure and deformation, Biot improved the consolidation theory of Terzaghi and introduced the effective stress coefficient. Such research suggests that the pore pressure gradually dissipates until 0 with the increase of the consolidation degree during the drainage consolidation of saturated clay, and the saturated soil sample is in the elastic state. However, by considering the viscous deformation of the soil skeleton, some researchers argue that the volume change caused by the pore water pressure change in the Terzaghi theory is just the initial consolidation of the soil samples. What's more, due to the deformation of the soil skeleton, under the fixed pressure, the clay will undergo second consolidation.

Based on the division of first consolidation and second consolidation, the consolidation analysis of clays is divided into two parts: Terzaghi theory is adopted in analysis of the consolidation process of pore water pressure dissipation; creep theory is adopted in analysis of the secondary consolidation stage. Sun Mingqian found that selecting the different end time of first consolidation, the second consolidation settlement calculated over a long period of time would be very different. It turned out that the consolidation analysis depended on the researcher's experience to a certain extent.

In order to reduce the dependence on the researcher's experience, it is considered that during the whole compression process, the deformation and drainage processes affect and adapt to each other in this paper. It means that the gradual removal of pore water in the soil, the pore volume reduction of the soil skeleton particles and gradual transference and adjustment of pore water pressure exist at the same time during the consolidation of clays. Then, a one-dimensional consolidation model describing the whole process of consolidation is proposed in this paper. And the first consolidation and the second consolidation are no longer distinguishable in the consolidation analysis of clays. In order to describe the rheological properties during clay consolidation, part of the one-dimensional consolidation model is based on the clay elastoplastic viscous model proposed by predecessors (yin, 2002 and sekiguch, 1976). The results show that the one-dimensional consolidation process of clay can be well described by the proposed consolidation model in this paper.

2. The governing equation of consolidation clay

In the one-dimensional drainage consolidation of the clay, the total load applied to the clay remains constant, and the load is shared by the clay skeleton and the pore water. The external load is equal to the sum of the pressure loaded on soil skeleton and pore pressure. The pressure loaded on soil skeleton is called effective stress of clay. Compressive stresses and strains are taken as positive.

Referring to Terzaghi's consolidation theory and Biot consolidation theory, the properties of the clay are assumed to be as follows:

1) Clay is isotropic.

2) Clay deformation is small.

3) The seepage in clay follows darcy law.

4) The clay only undergoes vertical compression and vertical seepage.

5) The solid and liquid phases of the clay are incompressible.

2.1. Continuity Equation

As the deformation of the clay is small, the geometrical equation of deformation can be expressed as:

$$\varepsilon_z = \frac{\partial u_z}{\partial z} = \varepsilon_v \tag{1}$$

Because the one-dimensional consolidation of clay is in accordance with the principle of material balance, the decrease of clay volume is equal to the outflow of fluid volume. The continuous equation of seepage of clay can be obtained,

$$\frac{\partial \varepsilon_z}{\partial \varepsilon} = \frac{\partial q_z}{\partial z} \tag{2}$$

The seepage in the clay conforms to the Darcy law:

$$q_z = -\frac{k}{\gamma_w}\frac{\partial u}{\partial z} \tag{3}$$

Substituting equation (3) into equation (2), the continuous equation of clay can be obtained:

2.2. Stress-strain relationship

In this section, the stress-strain relationship of the clay is mainly determined. According to the above assumptions, the deformation of the clay is mainly composed of two parts, the elastic-plastic deformation and the viscoplastic deformation. The elastic-plastic deformation part can be written as:

$$\varepsilon_v^{ep} = \varepsilon_{v0}^{ep} + \frac{\lambda}{V} + In\left(\frac{P_m'}{P_{m0}'}\right) \tag{5}$$

For the viscoplastic part of clay, there have been various types of viscoplastic models have been proposed, which can be divided into three categories. The first category is the component model, such as: Kelvin model, Burgers model, etc. These models use different components to simulate the rheological properties of rock and soil, and replacing the original components by new non-linear rheological components to simulate non-linear creep. The second category is the empirical model, whose physical meaning is unclear, but the form is simple, what's more, easy to understand and apply. For example, the yin model and the sekiguch model, these model generally thought that the relation of viscous deformation and time is logarithmic. The third model is the yield surface model (Niemunis1996, Chen Yuanhong 2002), which is mainly a three-dimensional rheological model. It is different from the first and second types of rheological models (mainly one-dimensional model). The main feature of this model is the yield surface, which is used in transforming the volume stress rheological equation into partial stress rheological equation. In this paper, empirical model and component model are more applicable compared to the yield surface model, because the research focuses on one-dimensional clay consolidation.

Component model that describes the theory of linear rheology has been relatively perfect. However, the establishment of non-linear components has no uniform standard, which limits the application of component model in nonlinear rheological research. And the nonlinear rheological phenomenon of clay is obvious. Therefore, the research that describes the rheological behavior of clay with component model is little and the form is not unified (Ma Bo Ning 2013, Qi Ya Jing 2012, Wang Zhongwen 2010). Compared to the component model, the model which is used to describe the rheology of clay is mainly empirical model, such as yin model and sekiguchi model. In this paper, the clay viscoplastic model is based on the empirical model.

yin model

Creep strains can be described by(Yin1999)

$$\varepsilon_v^{vp} = \frac{\psi}{V} In(1+\frac{t}{t_0}) \tag{6}$$

Where $\frac{\psi}{V}$ and t_0 are two material parameters.

At t = 0, the specific volume plots on the normal compression line at V_m=V_{ncl}. At this time, the clay is in the elastic-plastic stage. After the elastoplastic stage, the clay is in the viscoplastic state, and V_m is linearly related to the logarithm of time t.

1. sekiguchi model

Sekiguchi (1974) has extend the stress-strain-time model proposed by Murayama, Sekiguchi and Ueda (1974) to include the time-dependency of dilatancy of normally consolidated clays and obtained a relation predicting the time-dependent variation of volumetric strain under axi-symmetric conditions of sustained loading. The relation is rewritten here in the form:

$$\varepsilon_v = \frac{\lambda}{1+e_0} In\left(\frac{\sigma_m'}{\sigma_{m0}'}\right) + D(\eta-\eta_0) + \frac{3}{2}\overline{H_0}\left\{D + \frac{\lambda}{(1+e_0)N}\right\} xIn\left\{\left(\frac{\partial\varepsilon_v}{\partial t}\right)_{\sigma_{m0}',\ \eta_0} / \left(\frac{\partial\varepsilon_v}{\partial t}\right)_{\sigma_m',\eta}\right\} \tag{7}$$

where λ is the compression index, D the coefficient of dilatancy (Shibata,1963), $\overline{H_0}$the relaxion spectrum of a box –type which is normalized by the consolidation pressure, N the extra stress ratio, $\left(\frac{\partial\varepsilon_v}{\partial t}\right)_{\sigma_{m0}',\ \eta_0}$ the volumetric strain rate after the change of loading, and $\left(\frac{\partial\varepsilon_v}{\partial t}\right)_{\sigma_m',\eta}$ the volumetric strain rate after the change of loading.

Through the analysis of the above two models, it is found that although the assumptions and model parameters proposed by the respective models are different, the relationship between the viscoplastic deformation and the time is generally considered to be logarithmic in the models. In this paper, the viscoplastic deformation and the time were assumed to obey the following relationship:

$$\varepsilon_v^{vp} = \frac{\psi}{V} In\left(1+\alpha t\right) \tag{8}$$

If $\alpha = \frac{1}{t_0}$, then the model is equivalent to the yin model.

In the above equation, if the time approaches infinity, the strain approaches the infinity, which is clearly contradictory to the fact. Therefore, it is considered that the parameter ψ is not fixed, but time-related. Assume that the ultimate strain of clay is ε_{vm}^{vp},

$$\lim_{t=\infty} \varepsilon_v^{vp} = \lim_{t=\infty} \frac{\psi}{V} In(1+\alpha t) = \varepsilon_{vm}^{vp} \tag{9}$$

According to the above equation, and referring to clay model proposed by yin (yin,1999), we believe that the parameter $\psi$and time meet the following relationship:

$$\frac{\psi}{V} = \frac{\dfrac{\psi_0}{V}}{1+\dfrac{\psi_0}{V\varepsilon_{vm}^{vp} In(1+\alpha t)}} \tag{10}$$

In this paper, it is considered that the elastic strain is produced simultaneously with the viscoplastic strain. Thus, the stress and strain in the consolidation process of clay conform to the following relationship:

$$\varepsilon_v = \varepsilon_{v0} + \frac{\lambda}{V} In\left(\frac{P_m - u}{P'_{m0}}\right) + \frac{\psi}{V} In\left(1+\alpha t\right) \tag{11}$$

The partical derivative of the above formula is:

$$\frac{\partial \varepsilon_v}{\partial t} = \frac{-\lambda}{V\left(P_m - u\right)} \frac{\partial u}{\partial t} + \frac{\dfrac{\psi_0}{V}}{\left(1+\dfrac{\psi_0}{V\varepsilon_{vm}^{vp}} In\left(1+\alpha t\right)\right)^2} \left(\frac{\alpha}{1+\alpha t}\right) \tag{12}$$

By substituting equation (12) into equation (4), the consolidation formula can be obtained:

$$\frac{\partial \varepsilon_v}{\partial t} = \frac{-\lambda}{V\left(P_m - u\right)} \frac{\partial u}{\partial t} + \frac{\dfrac{\psi_0}{V}}{\left(1+\dfrac{\psi_0}{V\varepsilon_{vm}^{vp}} In\left(1+\alpha t\right)\right)^2} \left(\frac{\alpha}{1+\alpha t}\right) = -\frac{k}{\gamma_w} \frac{\partial^2 u}{\partial z^2} \tag{13}$$

The solution of the above equation shows that the pore pressure increases with the increase of time and strain, which is opposite to the fact that the pore pressure of clay dissipates with the increase of time and consolidation degree. So there is a mistake in the consolidation equation and need to be fixed. In the previous research, it is generally considered that rheological behavior does not exist in the main consolidation process, which indicates that when the pore pressure is greater, the rheological phenomenon is not obvious. Therefore, for the rheological parameter, we make the following assumption:

$$\alpha = \alpha_0 \left(1 - \frac{u}{P_m}\right) \tag{14}$$

Then, we can get the equation:

$$\frac{\partial \varepsilon_v}{\partial t} = \frac{-\lambda}{V\left(P_m - u\right)} \frac{\partial u}{\partial t} + \frac{\psi_0}{V} \frac{\alpha - \dfrac{\alpha_0}{P_m} \dfrac{\partial u}{\partial t}}{1+\alpha t} \left(\frac{1}{\left(1+\dfrac{\psi_0}{V\varepsilon_{vm}^{vp}} In\left(1+\alpha t\right)\right)^2}\right) \tag{15}$$

By substituting equation (15) into equation (4), the consolidation equation can be obtained:

$$\frac{\partial u}{\partial t}\left(\frac{\lambda}{V(P_m-u)} + \frac{\psi_0}{VP_m}\frac{\alpha_0}{1+\alpha t}\left(\frac{1}{\left(1+\dfrac{\psi_0}{V\varepsilon_{vm}^{vp}} In\left(1+\alpha t\right)\right)^2}\right)\right) = \frac{k}{\gamma_w}\frac{\partial^2 u}{\partial z^2} + \frac{\psi_0}{V}\frac{\alpha}{1+\alpha t}\left(\frac{1}{\left(1+\dfrac{\psi_0}{V\varepsilon_{vm}^{vp}} In\left(1+\alpha t\right)\right)^2}\right) \tag{16}$$

2.3. The boundary and initial condition

It is necessary to increase the boundary condition to solve the consolidation equation. This research assumes that the thickness of the consolidation clay is h, the bottom of clay is impermeable, the top of clay is the drainage layer, and the initial pore pressure is evenly distributed.

Then, the boundary conditions are:

$$\left.\frac{\partial u}{\partial z}\right|_{z=H}=0,\ u|_{z=0}=0 \tag{17}$$

The initial condition is:

$$u|_{t=0}=u_0 \tag{18}$$

The pore pressure and the final settlement in the clay at any consolidation time can be obtained by solving the governing equations 16, 17 and 18.

2.4. The Solution of Governing Equation

Due to the governing equations presented in the previous section appear too complex to yield an exact solution, so this study decides to use the finite difference method to solve it.

The clay thickness is H, the step size of Z direction and T direction is $\triangle$Zand $\triangle t$. For the sake of simplicity, record (k, j) = (z_k, t_j), u (k, j) = u (z_k ,t_j).

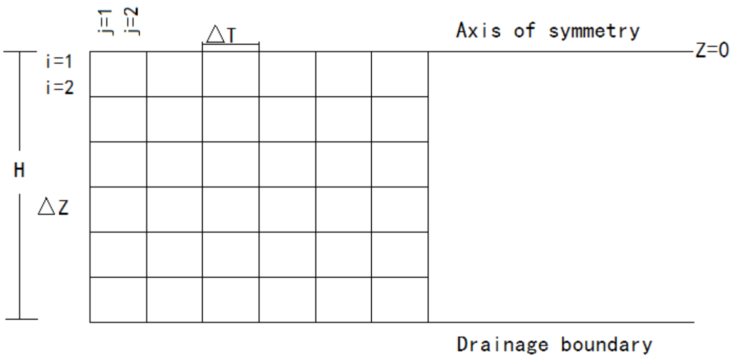

Figure 1. Finite difference grid

In the grid interior point (k, j), use the center difference quotient formula:

$$\begin{aligned}\left.\frac{\partial^2 u}{\partial z^2}\right|_{(k,j)}&=\frac{u\,(k+1,j)-u\,(k,j+1)-u(k,j-1)+(k-1,j)}{\triangle z^2}\\ \left.\frac{\partial u}{\partial t}\right|_{(k,j)}&=\frac{u(k,j+1)-u(k,j)}{\triangle t}\end{aligned} \tag{19}$$

By substituting equation 19 into equation16, the formula can be obtained:

$$\begin{aligned}&u(k,j)=u(k,j-1)\ +\frac{k\triangle t}{(\frac{\lambda}{V\,(p_m-u)}+\frac{m}{p_m}\alpha_0)\gamma_w}\frac{u(k+1,j-1)-2u(k,j-1)=u(k-a,j-1)}{\triangle z^2}+\frac{m\alpha\triangle t}{\left(\frac{\lambda}{V\,(P_m-u)}+\frac{m\alpha_0}{P_m}\right)}\\ &\alpha=\alpha_0\left(1-\frac{u(k,j-1)}{P_m}\right)\\ &m=\frac{\psi_0}{V}\frac{1}{1+\alpha t}\left(\frac{1}{1+\frac{\psi_0}{V\varepsilon_{vm}^{vp}}In(1+\alpha t)^2}\right)\end{aligned} \tag{20}$$

The above equation is the differential equation for one-dimensional consolidation equation.

In the upper boundary, use the backward difference quotient in replacing partial derivative, obtain the approximate difference of the boundary condition

$$\left.\frac{\partial u}{\partial z}\right|_{(H,\,j)} = \frac{u(H,j) - u(H-1,j)}{\triangle z} = 0 \tag{21}$$

3. Determination of parameters in the theory

As can be seen from equation 20, the one-dimensional consolidation equation mainly contains the following parameters:$\lambda, \psi_0, \alpha_0$. This section is mainly about how to obtain the values of these parameters by experiment.

3.1. Determination of parameter λ

The term λ is similar to that used in Modified Cam-Clay. When the compression experiment is carried out on the normal-consolidated clay, the relationship curve between the compressed volume of clay and the effective stress can be obtained. This relationship is called the normal consolidation line. The normal consolidation line (e-lnp') in the compression experiment is a straight line whose slope is the parameter λ, and Figure 2 shows the reference diagram for this relationship(Lu Tinghao 2006). Thus, the parameter λ can be obtained by the compression experiment of the normal consolidation clay.

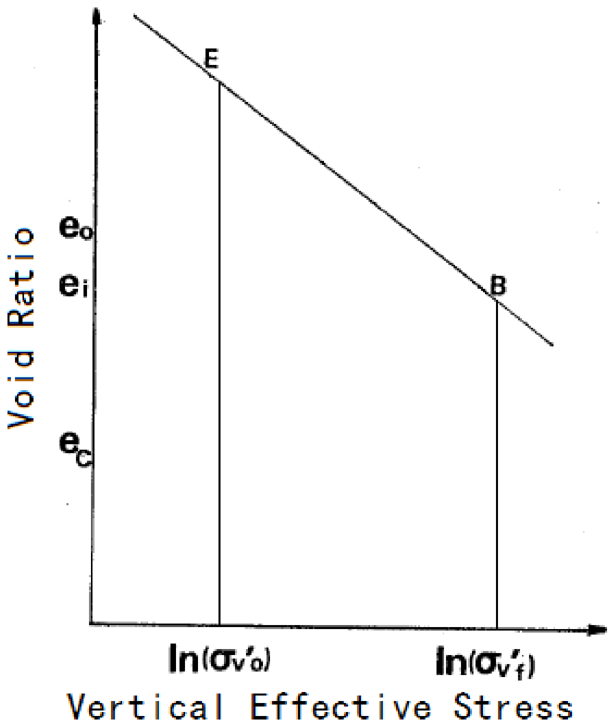

Figure 2. Compression experiment

3.2. Determination of ψ, α_0

The terms ψ, α_0 are material constant parameters. The creep experiments show that the strain of clay is linear with the logarithm of time. And the value of the parameters ψ_0 *and* α_0 can be obtained by fitting the creep experimental data of normal consolidation clay. Figure 3 shows the reference diagram for this relationship (Lu Tinghao 2006). Because of the large amount of pore pressure and its change in the early stage of creep experiment, when fitting the experimental data, the experimental data of latter stage of creep should be used and the creep strain of this moment is dominated by viscoplasticity.

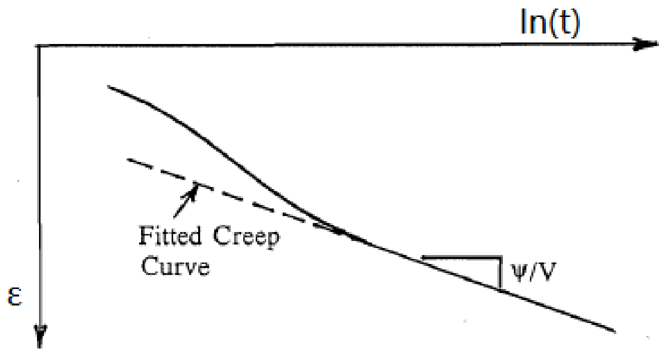

Figure 3. Creep experiment

4. Validation on one-dimensional consolidation experiment

4.1. Laboratory equipment

In this paper, the rheological tests of artificial clay were carried out in the laboratory according to the research demands. Compared with the field experiment, the indoor experiment has many advantages: more repeated times, less cost, easy for long-term observation, easy to control environmental factors and test conditions, and easier to highlight the main factors to eliminate the influence of secondary factors.

The test device is improved on the basic of original triaxial rock mechanics testing unit. Experimental equipment is shown in Fig.1, its main parts are followed:

1)Pressurization and constant pressure system

2)High pressure sealed system

3)Displacement measurement system

Pressurization and constant pressure system has two passages; a constant axial load is applied to the rock sample by jack through one passage and a constant confining pressure through the other one. By the time the applied pressure is showed in the digital display.

The displacement is measured by displacement sensor whose accuracy is 0.01mm. The results are displayed by numbers

Figure 4. The consolidation testdevice

4.2. Experimental samples

The artificial cores are used to simulate the one-dimensional consolidation. The research adopt the recipe of 89.5% Bentonite + 0.5% Na_2CO_3 solution + (10-X)% sand(200 mesh) + X% water to make the samples. The samples were made using conventional steel ring blades (6.18 cm in diameter and 2 cm in height) in a volume of about 60 cm^3 and prepared by the compact sample method. Before the test, extracting air in the sample and making it saturated. The test conditions of each sample to be consistent.

4.3. Consolidation experiment

The sample is double-sided drain. Single-stage loading method is used for test. The load is 25kPa. The indoor test is limited by the number of samples, time and test equipment. And long test process will make sample disturbance, affecting the test accuracy and other conditions of the constraints. So the test is not suitable for a long test cycle. At the same time, according to the previous research experience, shorter test time can achieve the desired goal, get more meaningful conclusions. So the loading time is 24 hours. The results are as follows:

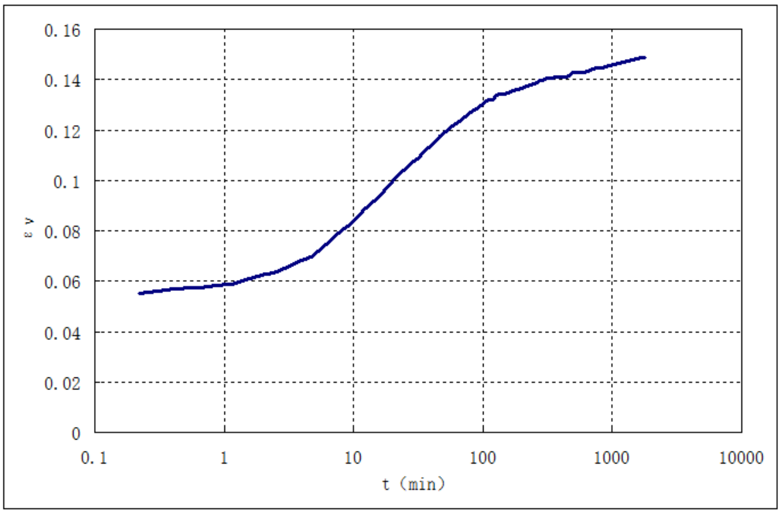

Figure 5. The relationship graph between the clay strain value and the time

4.4. Numerical calculation and analysis

According to the compression experiment and the creep experiment, the parameter values in the consolidation equation can be obtained as follows:

Table 1. Parameters in rheological model

λ	ψ_0	α_0	ε_{vm}^{vp}	K/γ_w
0.0126	0.03	0.0283	0.03	$1.13*10^{-3}$

It should be noted that ε_{vm}^{vp} and K/γ_w, these two parameter values are difficult to obtain directly from the compression experiment and the creep experiment. Therefore, the results of the consolidation experiments need to be fitted to obtain the specific values of these parameters. The results of the consolidation experiment are calculated with the rheological consolidation model and the Terzaghi model, and they are shown in Fig6.

By comparing the results of the rheological consolidation model and the consolidation experiment, it can be found that there is a certain error when the time is short, such as within 1h. The change of permeability should be responsible for the error. When the time is long, the permeability change is small, and then the rheological model can be a wonderful simulation of the experimental results. The Terzaghi model is mainly used to describe the main consolidation process of clay. It is difficult to use the Terzaghi model to simulate the whole consolidation process

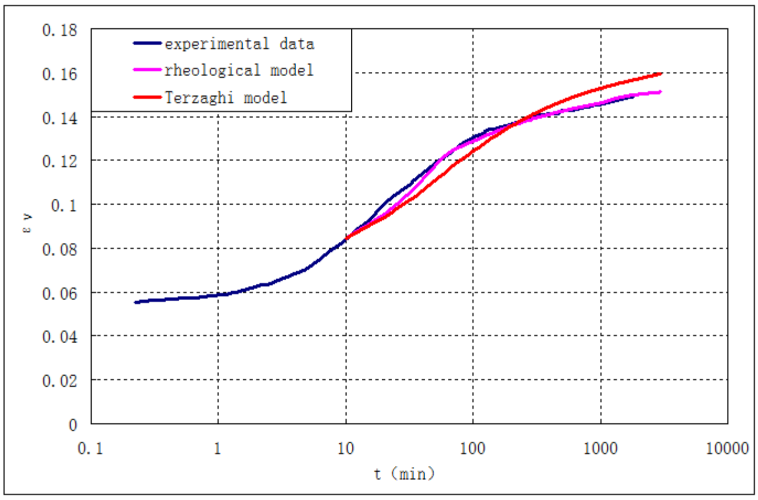

Figure 6. Comparison graph of clay strain value and time

of clay, and there is a great error in the simulation process by comparing the results of the Terzaghi model and the consolidation experiment. One of the reasons for the error is that the permeability and compressibility are changing with time. And another important reason is the hypothesis in Terzaghi model that the clay is in an elastoplastic state.

5. Conclusion

1. The clay elastic-plastic viscous model proposed by yin is modified, and the stress-strain relationship in modified model can better describe the consolidation behavior of clay.

2. On the basis of the modified model, a one-dimensional consolidation equation with rheology of the clay is deduced. The equation can describe the consolidation behavior of one-dimensional clay well.

3. The proposed rheological consolidation model overcomes the problem to distinguish the first and second consolidation process, which reduces the dependency on experience for the consolidation analysis calculation.

4. Due to the change of the permeability in the consolidation process, the rheological consolidation model has some error in describing the initial consolidation, which should be taken into account in the follow-up study.

6. Acknowledgments

This work was supported by the National Oil and Gas Major Project of China (Grant no. 2016ZX05028001-01) and National Program on Key Basic Research Project “973” Program (Grant no. 2015CB251202).

7. Appendix

List of symbols

ε_z − *axial strain*
z, u_z − *displacement, axial displacement*
ε_v − *volume strain*
t − *time*
q_z − *fluid volume*
k − *permeability*
γ_w − *specific gravity of water*
u − *pore* − *water pressure*
ε_v^{ep} − *elastic* − *plastic volume strain*
ε_{v0}^{ep} − *volume strain at* $'_m = '_{m0}$
λ − *slope of virgin compression line*
V − *specific volume, volume occupied by unit volume of solids*
P_m' − *mean effective stress under isotropic stres*sin*g*
P_{m0}' − *model parameter*
ε_v^{vp} − *viscoplastic creep strain*
ψ, ψ_0 − *creep parameter*
t_0 − *model parameter*
α, α_0 − *model parameter*
ε_{vm}^{vp} − *model parameter*
u_0 − *initial pore* − *water pressure*

8. References

1. Terzaghi K, Peck R B, Mesri G. Soil mechanics in engineering practice[M]. John Wiley & Sons, 1996.
2. Biot M A. General theory of three-dimensional consolidation[J]. Journal of applied physics, 1941, 12(2): 155-164.
3. Liu Mingqian. Research on Rheological and Consolidation Properties of Tianjin Coastal Soft Soil[D]. Jilin University of China, 2016.
4. Crawford C B. Interpretation of consolidation tests [J]. Journal of Soil Mechanics and Foundation Division, ASCE, 1964, 90(5): 87-102.
5. Casagrande, A. The determination of the preconsolidation load and its practical significance[C]. Proc.I st ICSMFE, 1936, 3: 60-64.
6. Qian Jiahuan, Application of Rheology Theory in Soil Mechanics [C]. Selected papers of the fourth national conference on soil mechanics and basic engineering, China Construction Industry Press,1986.
7. Qian Jiahuan, Wang Shengyuan, Guo Zhiping. Application of Rheology Theory in Soil Mechanics [C]// Selected papers of the national conference on soil mechanics and basic engineering, China Construction Industry Press. 1983.
8. Liu Shiming, Zeng Guoxi. On the secondary deformation of soft clay[J]. Journal of Zhejiang University (Engineering Science), 1990(6):840-848.
9. Yin J H, Zhu J G, Graham J. A new elastic viscoplastic model for time-dependent behaviour of normally and overconsolidated clays: theory and verification[J]. Canadian Geotechnical Journal, 2002, 39(1): 157-173.

10. SEKIGUCHI H, TORIIHARA M. Theory of one-dimensional consolidation of clays with consideration of their rheological properties[J]. Soils and Foundations, 1976, 16(1): 27-44.

11. Liu Xiliang. Principles of soil mechanics [M]. China University of Mining and Technology Press, 2015.

12. Ma Boning. Research on Rheological Consolidation of Soft Clayey Soils in Dual Scale[D]. Zhejiang University, 2013.

13. Qi Yajing, Jiang Qinghui, Wang Zhijian. 3D Creep Constitutive Equation of Modified Nishihara Model and its Parameters Identification [J]. Chinese Journal of Rock Mechanics and Engineering, 2012, 31(2):347-355.

14. Wang Zhongwen, Yuan Zhiqiang, Li Bin. Study on Creep Characteristic of Tertiary Argillaceous Rock in Loess Area [J]. Chinese Journal of Rock Mechanics and Engineering, 2010, 29(s2):004008-4015.

15. Niemunis A, Krieg S. Viscous behaviour of soil under oedometric conditions [J]. Canadian Geotechnical Journal, 1996, 33(1): 159-168.

16. Chen Yuanhong, Hong Baoning, Gong Daoyong. Modified Cambridge visco-elastic-plasticity model considering rheology of soil [J]. Journal of Hohai University (Natural Science Edition), 2002, 30(5):44-47.

17. Bjerrum L. Engineering geology of Norwegian normally-consolidated marine clays as related to settlements of buildings[J]. Geotechnique, 1967, 17(2): 83-118.

18. Yin J H, Zhu J G. Measured and predicted time-dependent stress-strain behaviour of Hong Kong marine deposits[J]. Canadian Geotechnical Journal, 1999, 36(4): 760-766.

19. Li Ronghua. Partial differential equation numerical solution (second edition) [M]. Higher Education Press, 2010.

20. Lu Tinghao, Liu Zude, Chen Guoxing. Advanced soil mechanics [M]. Machinery Industry Press, 2006.