A Research Study on the Consolidation and Creep Structural Model of Tianjin Coastal Soft Soil

Sun Ming-Qian, Wang Qing*, Ruan Yun-Kai, Dong Jia-Qi, Xiao Guang-Ping, Xu Xin-Chuan

Construction Engineering College, Jilin University
Changchun 130000, China
wangqing@jlu.edu.cn

Abstract — As reclamation project is widely applied in Tianjin Binhai New Area, it is very significant to research the consolidation and creep properties of soft soil foundation. One-dimensional Secondary consolidation experiment and quantitative analysis of microstructure on the soft soil with vacuum preloading treatment in Tianjin Marine Economic Area was carried out. Based on Terzaghi consolidation theory, modified Singh-Mitchell empirical creep model were used to establish new one-dimension rheological consolidation equations. Furthermore, quantitative parameters of microstructure and the creep parameters are combined to analyze the relationship between consolidation and structural changes of soft soil. The calculation results about different stress levels and different depth of specimens are very close to the experiment results. Comparing the results, it indicates that this new one-dimension rheological consolidation equation can reflect the stress-strain-time relationship of soft soil, and it is applicable for the soft soil foundation in Tianjin Marine Economic Area.

Keywords - soft soil foundation; creep; microstructure; Terzaghi consolidation theory; Singh-Mitchell empirical creep model

I. INTRODUCTION

With the rapid development of Chinese economy, the shortage of land resources has become one of the major factors that restrain urban growth. In order to acquire new land resources, coastal areas mainly undergo land reclamation using sludge and silt obtained through offshore dredging. Numerous projects have been carried out on the foundations that have been built on these reclamation lands. Since early 21st century, a large-scaled land reclamation foundations that have been built on these reclamation lands. Dredging. Numerous projects have been carried out on the reclamations using sludge and silt obtained through offshore land resources, coastal areas mainly undergo land factors that restrain urban growth. In order to acquire new shortage of land resources has become one of the major project has been conducted in the Binhai New District of Tianjin. As the material source used in this project is small grain, high cohesive soil content, and low permeability, etc., hard formation has been found on the foundation surface of the reclamation, whereas soft soil of flow plasticity exists in the lower part. The consolidation and creep of soft soil is the important factor that needs to be considered emphatically in construction projects. Because of the significant rheological characteristic of soft soil, the reclamation soft soil foundation remains rather low after draining and consolidation. The subsidence of the building above it is not able to stabilize for a long time. In other words, the subsidence is still developing even if the pore pressure has already disappeared according to the consolidation calculation. In the course of time, creep takes place obviously, which means secondary consolidation occurs. The secondary consolidation subsidence of soft soil is an important topic in soil mechanics. It imposes crucial influence on the consolidation of soil, the stability of slope or the bearing capacity of foundation, affecting the long-term stability of soft soil foundation and the security of the upper structure of the base. For instance, referring to the ground subsidence monitoring, the maximum annual subsidence value within Binhai is 68mm, and the dimension of the negative elevation is as large as 8km². Inside the district, the Nanjiang Port area still goes through approximately 30mm of ground subsidence after ten years of the reclamation [1]. Thus, studying the characteristics of the consolidation and creep of reclamation soft soil in Binhai New District of Tianjin, along with grasping the rules of its stress as well as deformation, provides the solution of actual problems in reclamation with references; concurrently, it is of great significance to the evaluation of the long-term stability, safe operation as well as post-construction subsidence prevention of the soil and the structural objects.

Numerous experiments and theoretical researches have been done by scholars all over the world regarding the consolidation and creep characteristics along with secondary consolidation subsidence of soft soil. In 1925, Terzaghi proposed the one-dimensional consolidation theory of saturated soil [2], which laid the foundation for the quantitative analysis of the process of soil consolidation, and became one of the most widely applied theories in geotechnical engineering. Nevertheless, such theory was based on a large number of simplified assumptions, causing its calculated values alienate from real circumstances of projects, hence it needed further research and improvement. One of the main reasons was that the one-dimensional consolidation theory of Terzaghi ignored the creep deformation of soil. Following Terzaghi, a lot of scholars carried out massive work on the model of soil creep, gaining huge achievements. For example, Buisman [3] (1935) represented the relationship between the subsidence of saturated cohesive soil and time with empirical formula in accordance to a large amount of experimental data²; whereas Merchant [4] (1964) referred to the theory of Terzaghi and took into account the rheological...
characteristics of soil when analyzing consolidation deformation, and proposed a consolidation differential equation that considers secondary consolidation effect through the multi-component rheological model; Bjerrum [5] (1967) put forward the concept of instant and delayed compaction, established the load-deformation-time relationship, believed that consolidation and creep occur simultaneously, proposed the theory of consolidation timeline, as well as discussed the calculation of soft soil consolidation deformation; Singh-Mitchell [6-7] (1968) built the soft soil empirical model based on tri-axial consolidation drained and undrained creep experiments; Yin and Graham [8] (1999) established a three-dimensional elastic and viscous plastic model (3D-EVP) in accordance with equivalent time concept and flow surface theory; Chen did enormous research on soil rheology and gained various crucial achievements, including proposing the three-way consolidation rheology theory of soil [9]; Xiao et al started to study the soft soil theories and engineering technologies of Binhai New District at a rather early time, during when they analysed the generation mechanism of the strength of reclamation soil structures, as well as building mathematical models of reclamation subsidence and self-consolidation [10]; through studying the creep characteristics and models of coastal soft soil, which was sampled from different regions of China for creep investigations, Wang put forward the compressive creep rate (CCR) concept as well a built a one-way constitutive model of compression that considers the properties of non-linear creep that was further proved to be found in the soft soil [11].

These results of studies above were from the macro mechanics point of view to discuss the problem of soil creep and consolidation. Few or no discussions were proceeded to explain the changes of soil microstructure [12-16], which means it is unable to understand the change rule of internal structure during the creep and consolidation process. In recent years, as there were many problems that the macro mechanics model cannot explain and solve in engineering practice, more and more scholars realized the importance and necessity of the stress-strain relationship basing on studying the microstructure of soft soil and set about studying the deformation and intensity of soft soil by analyzing the characteristics of its structure. As the special microstructure of reclaimed soft soil, the deformation and strength are influenced significantly by the damage of structure. To study the microstructure of reclaimed soft soil can not only help us to understand the mechanism of deformation and strength, but also can establish an accurate and reliable constitutive relation from the microstructure point of view. Most of previous studies about soil microstructure were mainly qualitative analysis. In recent years, the development of test methods and computer technology laid a basis on quantitative research for soil microstructure. There has been many achievements domestic and overseas since the 70’s. But as the complexity of soil microstructure, it is still in the exploratory stage and there is no unified and mature theory so far.

Based on the basic rheological principle of soft soil and Terzaghi consolidation theory, a stress-strain-time relation that can reflect the consolidation and creep characteristics of soft soil was established by analyzing the one-dimensional compression creep test results of reclaimed soft soil in Tianjin Marine Economic Area and Singh-Mitchell creep model. Further more, the microstructure and macro mechanics of soft soil were combined to research the change of microstructure in the creep and consolidation progress under different load, on the basis of microstructure quantitative research. The discussion of the relationship between consolidation of soft soil and its structure change laid a basis on establishing a time-effect model that reflects the deformation characteristics of soft soil consolidation, and provided a new method for soft soil foundation reinforcement.

II. ENGINEERING PROFILE

Research was conducted on the soft soil foundation in the Binhai New District, on eastern coast of Tianjin, China. The position of the study area is shown in Figure 1. The soil samples were extracted from three different depths, including 5m, 10m and 20m, each sample of which went through a series of one-dimensional consolidation experiments. Results revealed that the predominant components of the soft soil foundation in this reclamation area was soft cohesive soil, the basic parameters are shown in the following table.

Figure 1 Geographical position of the study area
SUN MING-QIAN et al: A RESEARCH STUDY ON THE CONSOLIDATION AND CREEP STRUCTURAL …

TABLE 1 BASIC PROPERTIES OF SOIL SAMPLE

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Depth h/m</th>
<th>Density ρ/g cm⁻³</th>
<th>Moisture content w/%</th>
<th>Void ratio e</th>
<th>Compression coefficient a₁/MPa⁻¹</th>
<th>Liquid index IL</th>
</tr>
</thead>
<tbody>
<tr>
<td>silt</td>
<td>5m</td>
<td>1.937</td>
<td>28.3</td>
<td>0.785</td>
<td>0.444</td>
<td>1.045</td>
</tr>
<tr>
<td>silty clay</td>
<td>10m</td>
<td>1.975</td>
<td>24.2</td>
<td>0.742</td>
<td>0.305</td>
<td>0.923</td>
</tr>
<tr>
<td>silty clay</td>
<td>20m</td>
<td>1.982</td>
<td>26.8</td>
<td>0.725</td>
<td>0.312</td>
<td>0.735</td>
</tr>
</tbody>
</table>

Soft soil has formed since the middle Holocene epoch, and it occurs widely in the Tianjin Binhai New District. Mainly containing mucky clay or mucky soil, the soft soil layer thickens gradually from west to east, and is generally thicker than 5 m. The thickest soil layer is more than 20 m thick. The soft soil of the Tianjin Marine Economic Area is typical unconsolidated soil, with high moisture content, high pore ratio, high compressibility, low strength, low stability, low permeability, and low engineering mechanical properties. Due to the engineering geological characteristics above, the soil layer is still undergoing self-weight consolidation. Considering the low permeability and its long history of formation, the consolidation process of the soil soft layer is mainly secondary consolidation settlement. The Tianjin Marine Economic Area is located in the Huanghua depression of the northeast fault basin in North China. The thickness of the Cenozoic strata is more than 4000 m. The thickness of the Quaternary strata is 300 m to 400 m. The soft soil layer includes artificial fill, dredger fill (Q₄ml), the Neocene (Q₄₃N), the upper Holocene (Q₄₃al), the middle Holocene (Q₄₂m), and the lower Holocene (Q₄₁h⁺al).

III. CONSOLIDATION AND CREEP CHARACTERISTICS OF SOFT SOIL

In this experiment, the WG single-lever consolidometer was used, two-way drainage was carried out on the soil sample, of which the height was 2 cm and the area was 32.2 cm². It was done in the form of hierarchical loading, including 25 kPa, 50 kPa, 100 kPa, 200 kPa and 300 kPa. Due to the time effect properties of soil creep, it is a rather lengthy delay process in actual projects. Also, indoor experiments are constrained by a range of conditions, involving limited time and equipments that can be used for the huge amount of soil sample, the considerably high sensitivity of reclamation soft soil, and that the prolong experiment process will cause destabilisation in the soil sample which leads to the empirical inaccuracy. Hence, such experiments are not compatible with long experimental durations. Meanwhile, according to the experience of previous scholars, shorter experimental durations can also achieve expected goals and derive rather meaningful conclusions. Therefore, the time interval between each loading level was set at the stabilisation of deformation, where 0.005 mm/d was the stability standard. In other words, providing that the daily compression did not exceed 0.005 mm, the next level of load could be put on. Please refer to Table 2 for detailed loading plan.

TABLE 2 CREEP TEST SCHEMES

<table>
<thead>
<tr>
<th>Depth/m</th>
<th>Hierarchical loading method/kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>25, 50, 100, 200, 300</td>
</tr>
<tr>
<td>10</td>
<td>25, 50, 100, 200, 300</td>
</tr>
<tr>
<td>20</td>
<td>25, 50, 100, 200, 300</td>
</tr>
</tbody>
</table>

Many scholars carried out massive research on the creep characteristics of soft soil, and summarized a large number of valuable empirical creep equations that are able to reflect the creep properties of soil under certain stress condition. As the experiment result indicates, when the creep stress was relatively low, linear relationship existed between the strain rate and time \( \langle \ln \varepsilon - \ln t \rangle \) in double-logarithmic coordinate. Based on this rule, Singh and Mitchell proposed the Singh-Mitchell creep formula:

\[
\varepsilon = A e^{\alpha t} \left( \frac{D}{t} \right)^m
\]

where \( D \) —— stress level, which is defined as \( D = (\sigma_1 - \sigma_3) / (\sigma_{1f} - \sigma_{3f}) \), \( f \) represents the time of damage; \( t_{1c} \) —— obtainable time unit; \( A, \alpha, m \) —— the constant of material for the creep experiment.

This paper conducted one-dimensional compressive creep experiment on the reclamation soft soil samples from different depths which has been vacuum preloaded. According to the results of the above experiment, the double-logarithmic curve of the relationship between strain rate and time was worked out, as shown in Fig. 2.
We can learn from Fig. 2 that strain rate and time presents a rather good linear relationship in the double-logarithm coordinate, hence its linear equation is:

\[
\ln \varepsilon = \alpha \ln \frac{t}{t_1} + \ln \varepsilon_{(t, \theta)}
\]

(2)

where \(\varepsilon_{(t, \theta)}\) —— the strain rate of a unit of time, which is the function of stress \(p\), equals the intercept of the double-logarithmic curve between strain rate and time; 
\(\alpha\) —— \(\alpha\) is the slope of logarithmic curve between strain rate and time, normally locating between -0.75 and -1.

Based on Fig. 2, \(\ln \varepsilon_{(t, \theta)}\), which indicates the intercept of curve, rises as the load \(p\) increases, hence a certain connection was supposed to exist between \(\varepsilon_{(t, \theta)}\) and \(p\). The double-logarithmic curve of the relationship between \(\varepsilon_{(t, \theta)}\) and stress \(p\) was depicted as Fig. 3.

In accordance with Fig. 3, there was a rather good linear relationship between the intercept of the double-logarithmic curve of strain rate and time and load \(p\), hence the following the fitting equation could be derived:

\[
\ln \varepsilon_{(t, \theta)} = \beta \ln p + \gamma
\]

(3)

where \(\beta\) —— \(\beta\) is the slope of curve between \(\varepsilon_{(t, \theta)}\) and \(p\).
\(\gamma\) —— \(\gamma\) is the intercept of curve between \(\varepsilon_{(t, \theta)}\) and \(p\).

Substitute eq. (3) in eq. (2), eq. (4) is generated:

\[
\ln \varepsilon = \alpha \ln \left(\frac{t}{t_1}\right) + \beta \ln p + \gamma
\]

(4)

which is

\[
\varepsilon = p^\beta \varepsilon^\alpha
\]

(5)

\(\alpha\) is called time effect coefficient. Many studies have shown that \(\alpha\) is different when the load \(\sigma\) has changed, and the relationship between \(\alpha\) and \(\sigma\) is very complicated.

As the structure of sample is loose before compression, the restructuring is relatively fast when certain initial load applies. As a result \(\alpha\) is bigger. And when the increment of load is not big enough to restructure rapidly, \(\alpha\) is smaller. When the increment of load is large and the total load reaches a certain value, \(\alpha\) increases gradually as the restructure continues. \(\alpha\) increases obviously when the load is large enough. Therefore, \(\alpha\) as the time effect coefficient of soft soil not only reflects the macro mechanical characteristics of creep and consolidation, but also reflects the ability of restructuring during compression progress. This feature of non-linear relationship between \(\alpha\) and \(\sigma\) can not be described by linear viscous unit. It is not simply concerned with the applied load, but has intrinsic connection with the special structure in soft soil. Therefore, it is necessary to study the changing rules of soft soil microstructure.

IV. MICROSTRUCTURE OF SOFT SOIL

The mechanical traits of creep and consolidation above can be explained essentially through the research of microscopic structure. In order to study the micro-structural changes of soft soil during creep and consolidation process under multi-stage load, microstructure quantitative analysis is required to describe the microstructure features of soft soil. Microstructure generally refers to the size, shape, arrangement, surface characteristics, connecting relationship of structural unit, and distribution characteristics of pores. Modern soil science considered the structural unit is the basic element of soil structure. The external shape of structural unit has significant profile. The soil deformation due to the movement, rotation or morphology changes of structural unit under compression. Therefore, it is important to study the spatial distribution of structural unit for soft soil deformation mechanism and its strength. Microstructure quantitative analysis techniques take scanning electron microscope (SEM) as a method of testing. Using statistical, nonlinear theory and computer technology to study structural unit and porosity, SEM image is obtained.
Quantitative analysis and evaluation of shape, orientation, pore characteristics and comprehensive features are conducted by studying SEM, providing quantitative structural parameters to build constitutive relations of soft soil on strength and deformation.

SEM and computer quantitative analysis of soft soil structure under multi-stage load in Tianjin Marine Economic Area were conducted, using microstructures quantitative analysis during creep and consolidation process. Typical SEM images were collected and spliced to increase the information of quantitative analysis and improve the reliability of structural parameters. The SEM photographs were scanned into the computer and processed by image software to eliminate deviations and clear the outline of structural unit.

Degree of orientation (Ω) is the ratio of area in vertical compression direction or parallel shear direction to the total area of structural unit, which indicates the orientation degree in two-dimensional microstructure SEM photographs. The bigger Ω is, the better the directionality is. Ω can describe the directionality of microstructure reasonably. The calculation formula of Ω can be presented as:

$$\Omega = \frac{A_1}{A}$$  \hspace{1cm} (6)

The orientation degree of soft soil in Tianjin is mainly composed of two particle size groups, which are 5–10 μm and 10–20μm, especially the 5–10μm particle size group. The orientation of particle size group 2–5μm increased slightly along with the increase of load. And the orientation of group 10–20μm was basically unchanged. The variation law of the overall orientation was the same with the change of the particle size group 5–10μm, which means the orientation degree of structural unit is mainly controlled by the particle size group 5–10μm.

As a kind of nonlinear theory, fractal geometry has become the most common method to describe irregular, discrete, nonlinear and fractured phenomenon, and has been widely applied in areas such as physics, biology, geological since the 70’s. Xiao (1990) made fractal analysis for the strength of weak intercalated in dam foundation of. Chen (1995) studied the fractal geometry of rock mass fracture network. The microstructure of soft soil is a kind of fractal structure with statistical similarity. Therefore the features of soft soil microstructure can be described quantitatively by statistical self-similarity approaches. Research results have shown that if r is the side length of grid, N(r) is the total number of the structural unit in long axis. In the double logarithmic coordinate system, lnN(r)-lnr is a linear relationship. C and Df is constant and -Df is the directional fractal dimension, which is the main index in fractal geometry. The smaller Df is, the better stereospecificity of microstructure is. The calculation formula can be presented as:

$$N(r) = C r^{-D_f}$$  \hspace{1cm} (7)

The directional fractal dimension of soft soil is gradually decreasing along with the increase of the load application, which means the directional property of soft soil structure strengthened gradually. The rule of stereospecificity changes as the difference of micro structure. The results of SEM quantitative analysis are shown in table 3.

<table>
<thead>
<tr>
<th>pore diameter (μm)</th>
<th>0.002</th>
<th>0.006</th>
<th>0.009</th>
<th>0.309</th>
<th>0.259</th>
<th>0.07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ω</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>25</td>
<td>30</td>
</tr>
</tbody>
</table>

As mentioned above, α can describe the one-dimensional consolidation properties of soft soil well, and the influencing factors of α is very complicated. This paper considers that α has intrinsic connection with microstructure of soft soil. Because of particularity structure, soft soil shows different mechanics properties under the external load application. The microstructure changes under load application, and the change is the reflection of soil deformation. That is to say, the change of microstructure is the essence of macroscopic deformation. In the research of microstructure characteristics under multiple load application, a good correlation was found between α and certain quantitative indicators of micro structure. Df and Ω have the best correlation with α. Df and α have a positive correlation. Ω and α have a negative correlation. α decreases along with the increase of Ω. Further more, α and Df/Ω have better correlation, as shown in figure 4. The ratio of Df and Ω is called microstructure factor, represented by M. M can reflect the directionality of structure unit. The bigger M is, the worse directionality is. Equally, M also can reflects the value of α. The bigger M is, the bigger α and the creep deformation rate are.

![Figure 4 Relationship between M and α](image)

The calculation formula by curve fitting in Fig.4 can be presented as below:

$$\alpha = aM + b$$  \hspace{1cm} (8)

a is the slope of curve and b is the intercept of curve between α and M. This formula expresses the internal relations between macroscopic mechanical properties and microstructure of soft soil.
V. CONSOLIDATION AND CREEP RELATION OF SOFT SOIL

Since Terzaghi created the classic theory of one-dimensional saturated soils consolidation in 1925, a huge development has been achieved in the theoretical research on foundation consolidation. According to Terzaghi, once the pore water pressure completely eliminated from the soil, the consolidation finished and the deformation terminated. As for the soft soil foundation consists of soft cohesive soil, however, when pore water pressure entirely disappeared but effective stress basically remained unchanged, the subsidence would enlarge over time, which means creep takes place; and the soft soil foundation subsiding phase was named as main consolidation subsidence. The creep deformation emerged in the secondary consolidation subsidence stage mainly indicates that when the stress stayed the same, the bound moisture in the soil moved slowly in a viscously flowing status, causing relevant changes in the bound moisture membrane and creep in the soil skeleton. Because the one-dimensional consolidation theory of Terzaghi was incapable of describing the creep deformation in the consolidation subsidence stage of the soft soil foundation, this paper established a new stress-strain-time relationship that could reflect the consolidation and creep of soft soil based on such theory.

In accordance with the soil routine compression experiment, the equation of compression coefficient ($a_1$) and compression modulus ($E_s$) could be obtained:

$$a_1 = \frac{\Delta e}{\Delta p}$$

(9)

$$E_s = \frac{\Delta p}{\Delta e} = \frac{1+e_s}{a_1}$$

(10)

Based on eq. (9) and eq. (10):

$$\Delta e = \Delta e(1+e_s) = e_p - e_s$$

(11)

$$e_s = e_s - \Delta e(1+e_s)$$

(12)

where \(\Delta e = e_s - e_p\)

\(\Delta e\)——the changes of pore ratio generated by consolidation;

\(\Delta e\)——the increase of strain generated by consolidation;

\(e_p\)——the initial pore ratio before consolidation;

\(e_s\)——the pore ratio when the main consolidation subsidence completed;

\(e_s\)——the pore ratio at the end of creep deformation;

\(e_s\)——the soil strain at the end of creep deformation;

\(e_p\)——the soil strain when the main consolidation subsidence completed.

Based on the basic assumptions of the Terzaghi theory, the changes of the pore volume \(V\) inside the micro unit \(dxdydz\) in the soil of the foundation should equals the moisture quantity \(Q\) in it within the period of \(dt\), as shown in Fig.5.

![Figure 5 Micro unit](image)

The change of \(V\) within the period of \(dt\):

$$dV = \frac{\partial V}{\partial t}dt + \frac{\partial V}{\partial t}dt = \frac{\partial (e_pV)}{\partial t}dt + \frac{\partial (e_pV)}{\partial t}dt$$

$$= \frac{1}{1+e_s} \left[ \frac{\partial (e_pV)}{\partial t} + \frac{\partial e_p}{\partial t} \right]dxdydzdt$$

(13)

Where \(\frac{\partial V}{\partial t}dt\) represents the change of micro unit pore volume at the main consolidation subsidence stage;

\(\frac{\partial V}{\partial t}dt\) is the change of micro unit pore volume after the main consolidation subsidence;

\(V_s = \frac{1}{1+e_s}dxdydz\) indicates the volume of the micro unit, does not change over time.

During the main consolidation subsidence phase, the basic assumed conditions of the Terzaghi theory remained unchanged, because the changes of pore ratio under lateral confinement is in proportion to the vertical effective stress, which means \(-de_p/\partial t = a_1\), while the compression coefficient \(a_1\) was a constant; according to the effective stress principle, the following equation could be derived:

$$\frac{\partial e_p}{\partial t} = \frac{-a_1}{\sigma_v} \frac{\partial (\sigma - u)}{\partial t} = a_1 \frac{\partial \sigma_v}{\partial t}$$

(14)

Based on eq. (12) and eq. (13):

$$\frac{\partial e_p}{\partial t} = \frac{\partial (e_s - \Delta e(1+e_s))}{\partial t} = -(1+e_s) \frac{\partial \Delta e}{\partial t}$$

$$= -(1+e_s) \frac{\partial e_s}{\partial t}$$

(15)

where \(e_s\)——the strain rate of soil after the completion of main consolidation subsidence.

According to eq.(13),(14) and (15):

$$dV = \left( \frac{a_1}{1+e_s} \frac{\partial \sigma_v}{\partial t} - \frac{\partial e_p}{\partial t} \right)dxdydzdt$$

(16)
In accordance to Darcy’s law, the change of \( Q \) (moisture quantity in the micro unit) in \( dt \) was:

\[
dQ = \frac{\partial Q}{\partial t} dt = \frac{k}{\gamma_c \varepsilon_c} \frac{\partial }{\partial t} dxdydzdt
\]  

(17)

where \( k \) —— the permeability coefficient of soil.

Because \( dQ = dV \), the following equation could be acquired:

\[
\frac{\partial u}{\partial t} = C \frac{\partial^2 u}{\partial z^2} + \frac{1 + \epsilon_0}{a_0} \epsilon_0 e^{\delta \Delta t + bt}
\]  

(18)

According to eq.(5),(8) and (18):

\[
\frac{\partial u}{\partial t} = \frac{1}{C} \frac{\partial^2 u}{\partial z^2} + \frac{1 + \epsilon_0}{a_0} \rho^n e^{\delta \Delta t + bt}
\]  

(19)

This differential equation can reflect the stress-strain-time relation and consolidation properties of soft soil. It is on the basis of Terzaghi one-dimensional consolidation theory, which is improved by Singh-Mitchell experience creep model, and combine microscopic structure and macroscopic mechanical together.

VI. CALCULATION OF DIFFERENTIAL EQUATION

In accordance to the result of the one-dimensional compressive creep experiment, the parameters \((a, \beta, \gamma, a, b)\) that the consolidation differential equation (19) requires can be worked out as mentioned in Section 4.1. The initial void ratio \((e_0)\) and the compression coefficient \((a_0)\) is shown in Table 1. Meanwhile, the value of the consolidation coefficient \((C)\) at different depths and loading effects are displayed in Table 4.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Parameter Values of Consolidation Differential Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth/m</td>
<td>P/kPa</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>300</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>300</td>
</tr>
<tr>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td></td>
<td>300</td>
</tr>
</tbody>
</table>

The consolidation differential equation (19) can be solved with the numerical approach. To present it in the forward difference format, the following equation can be derived:

\[
\frac{u^n - u^{n-1}}{\Delta t} = C \frac{u^{n-1} - 2u^n + u^{n+1}}{(\Delta z)^2} + \frac{1 + \epsilon_0}{a_0} \rho^n e^{\delta \Delta t + bt}
\]  

(20)

Subsequently, working out in the backward difference method, which is shown below:

\[
\frac{u^n - u^{n-1}}{\Delta t} = C \frac{u^{n-1} - 2u^n + u^{n+1}}{(\Delta z)^2} + \frac{1 + \epsilon_0}{a_0} \rho^n e^{\delta \Delta t} \delta (\delta - 1) \cdots (\delta - n + 2) e^{\delta \Delta t}
\]  

(21)

The unconditionally steady Crank-Nicolson difference mode is shown as:

\[
Au^{n+1} + (1 - 2A)u^n + Au^{n-1} = -Au^{n+1} + (1 + 2A)u^n - Au^{n-1} - \left[ \Delta t (\delta - n) B + 2B \right] e^{\delta \Delta t}
\]  

(22)

Where

\[
A = \frac{\Delta C}{2(\Delta z)^2}
\]

\[
B = \frac{1 + \epsilon_0}{a_0} \rho^n e^{\delta \Delta t} \delta (\delta - 1) \cdots (\delta - n + 1)
\]

In accordance with the differential equation of one-dimensional rheological consolidation (19), the secondary consolidation deformation of the soft soil sample of the reclamation, which was vacuum preloaded, was calculated under different depths and stress levels. Moreover, the strain-time relationship curve was drawn as well as compared to the test curve, as shown in Fig.6. Based on the graph, the result from the above equation was very close to the test value, which indicates that vacuum preloaded reclamation soft soil is suitable for Binhai New District while reflecting the relationship between the stress, strain and time of soft soil consolidation as well as creep.
consolidation parameters. The results of one-dimensional secondary consolidation tests show that the unidirectional compression creep strain rate and creep time of soft soil have good linear relationship in double logarithmic coordinate system. This conclusion accords with Singh-Mitchell experience creep equation. can describe the mechanics characteristic of one-dimensional consolidation and creep well, and reflect the adaptability of soft soil under load application.

2. Through microstructure quantitative analysis of soft soil in Tianjin Marine Economic Area, it can be seen that there is essential relation between macro mechanics properties and microstructure. The essential relation can be described by α and microstructure quantitative indicators. In this paper, M is a microstructure quantitative indicator which can reflect microstructure characteristics of soft soil. It can establish a good correlation with α, reveal the microscopic essence of consolidation preliminarily and lay a foundation for establishing a constitutive relation of soft soil based on the nature of deformation.

3. According to the test results, the secondary consolidation parameters and modified Singh-Mitchell creep model were used in the improvement of Terzaghi one-dimensional consolidation theory, taking into account the secondary consolidation deformation occurred during the secondary consolidation subsidence phase of the soft soil foundation. Further more, microstructure and macroscopic mechanical were combined to study the microstructure change during the progress of consolidation and creep under different load application on the basis of microstructure quantitative research. A suitable rheological consolidation differential equation for Tianjin coastal soft soil was established.

4. The differential equation of one-dimensional rheological consolidation based on Singh-Mitchell creep model derived calculated values that were fitting well with test values, reflecting the stress-strain-time relationship of soft soil foundation well. Furthermore, the effectiveness of such equation was validated. In addition, it was of few parameters and excellent applicability, and so on.

Acknowledgment
This work is supported by the Natural Science Foundation of China (No.41172236 and No.41402243) and Ph.D. Programs Foundation of Ministry of Education of China(2012061110054).

REFERENCES

DOI 10.5013/IJSSST.a.16.2B.04 4.8 ISSN: 1473-804x online, 1473-8031 print