Compression Behaviors of Marine Clay for Coastal Reclamation in Dalian, China

M. J. Jiang, N. Zhang, and J. D. Liu

Abstract

In the offshore areas of Dalian, China, a coastal reclamation project is ongoing for building an international airport. In the project, the possible excess settlement due to consolidation and creep of soil is one of the main concerns. In this paper, three series laboratory tests, i.e., conventional consolidation and rebounding tests, one-dimensional creep tests and triaxial creep tests were carried out to study the compression behaviors of the marine clay. All these tests were performed on undisturbed samples procured from the depth of 10 and 18 m below the seabed of Jinzhou Bay seabed. The compression and swelling indexes obtained from the conventional compression and rebounding tests show that marine clay presents much higher compressibility and special attention should be paid to the settlements in the project construction. The results of both one-dimensional and triaxial creep tests show that the creep deformation of soils increases with elapsed time and stress level. In addition, failure of soil hardly occurs in the process of creep and the soil deformation could eventually stabilize at any given stress level even in triaxial tests. At last, the stress-strain-time relationships were simulated to estimate the time-dependent behaviors of the marine clay.

Keywords

Marine clay • Compressibility • Creep • Stress-strain-time relationship

1 Introduction

In past decades, the coastal reclamation becomes more and more common in coastal area out of various purposes. These man-made lands directly rest on the marine deposits which are often featured by high water content, large void ratio, high compressibility and poor strength. Hence, the settlement and the stability are usually the main concerns in coastal reclamation projects. Actually, settlements often cause much more serious problems in marine engineering because the settlements may have exceeded the permissible limits when the soil is still strong enough to resist shear failure. Thus, in the design of the foundation treatment, the settlement always needs special attention.

It has been realized that there are two aspects involved in foundation settlements: consolidation and creep induced compression in soil. The former associates with increasing effective stress and pore water drainage. Terzaghi's theory and effective stress principle have been widely accepted in the evaluation of soil consolidation. And correspondingly, the layerwise summation method is generally used to estimate the foundation settlement in engineering. On the other hand, creep induced compression relates to the time-dependent behaviors of soil. The creep behaviors of soil have also been studied when the long term settlements of constructions

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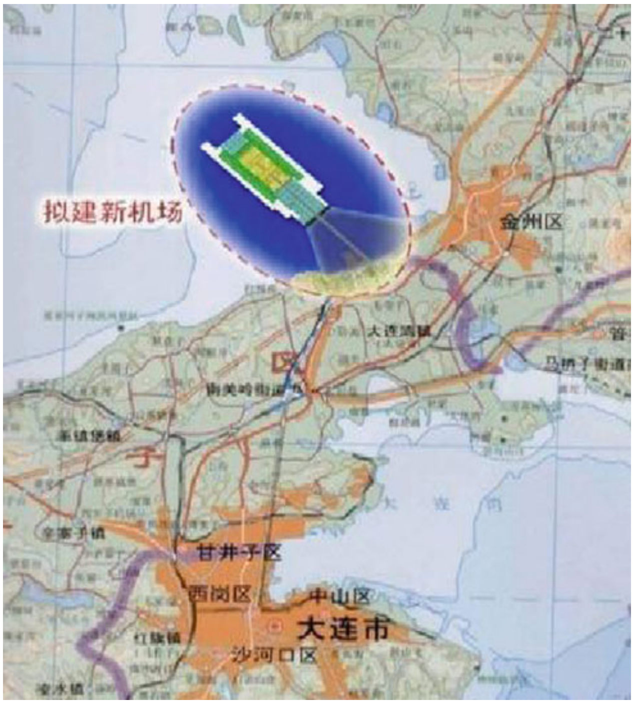

Fig. 1 The pictorial sketch of the coastal reclamation project

resting on soft clay (Bjerrum 1967; Leroueil et al. 1985; Mesri et al. 1997; Yin 1999) and reclaimed coastal (Miao 2008; Liu et al 2011; Chung 2002; Suneel 2008) was investigated. Developing a stress-strain-time relationship is the key problem in the estimation of the creep deformation which is still a controversial issue despite of the various attempts. So far, Singh-Mitchell creep model and Mesri creep model (Li 2001) are mostly used in geotechnical engineering. The differences between the two models lies in the description of stress-strain relationships. Singh-Mitchell model uses an exponential stress-strain relationship while Mesri model uses a hyperbolic relationship. The rheology tends to establish stress-strain-time relationship using element theory.

An ongoing coastal reclamation project locating in Dalian, China, is carried out for the construction of an offshore airport in the short run. It is for the first time that China constructs such an offshore airport independently. As shown in Fig. 1, the reclaimed land occupied about 22.89 km^2, with the length of 6540 m and the width of 3500 m, and the revetment is about 21440 m. The design altitude for the man-made land is 3.1 m, with the design high sea level of 1.06 m and the hundred-year extreme high sea level of 2.15 m. It is expected that the backfilled soil and rock could be as much as 17,368 m^3. This makes it one of the largest offshore airport projects worldwide, consequently raising quite a lot of geotechnical problems including stability and settlement.

In this paper, we investigate the compression behaviors of Dalican marine clay by consolidation tests and creep tests in laboratory. The stress-strain-time relationships for Dalian clay are developed using Mesri creep model based on the testing results. It should be pointed out that the native seawater with the salinity concentration of 0.05 g/ml was used in all tests in case of the influence of pore water system on soil compressibility.

2 Test Program and Soils Examined

2.1 Test Program

In laboratory, the soil compression behaviors were investigated by consolidation tests, and creep tests. The testing procedures are described in detail as follows.

Consolidation tests: The oedeometers were used to study the compressibility of soils due to consolidation by performing conventional 24 h consolidation tests. The consolidation loading increased from 50 to 1600 kPa in steps with the incremental ratio of 1.0.

Creep tests: One-dimensional and triaxial creep tests were carried out to study the time-dependent behaviors of soils. The specimens were also multi-stage loaded in both types creep tests. The one-dimensional creep tests were performed in oedometer and the loading was in the range of 50 to 1600 kPa with incremental ratio of 1.0. At each stage, the specimen deformation would observed until it was less than 0.01 mm in 24 h when the loading was increased to the following stage. The stress-path controlled instrument was used for the triaxial creep tests in which the specimens were firstly consolidated at the confining pressure of 100, 200, 400, 800 kPa respectively before creep testing. Triaxial creep tests were done under the drainage conditions. The specimen was first continuously loaded until the pre-designed deviator stress was attained. Then the axial strain and the volume change would be observed at this stress level until the axial deformation in 6 h was less than 0.01 mm when the deviator stress could increase to the next stage. In triaxial creep tests, the specimen would be loaded until the failure was observed in either loading or creep process.

Note that all the tests were done at the temperature of 20 ± 1 °C in case of the influence of temperature variation on soil creep behaviors.

2.2 Samples

Table 1 presents the general geological information of the area where the coastal reclamation project locates. The overlay mainly consists of sea shore facies, intermediate

Table 1 Hydrological engineering geology for clay in Dalian, China

Chronologic	Lithologic characters	Depth (m)	Thickness (m)	Formation
Holocene	Muddy silty clay	0–10	0–10	Sea shore facies
	Gray mild clay	11–22	0–12	

Table 2 Physical and basic mechanical parameters of Dalian clay

No.	Description	ω/%	ρ_d/g cm^{-3}	Liquid limit/%	Plastic limit/%	Void ratio	C_c	C_e
C10	Muddy silty clay	63.90	1.66	64.30	20.50	1.666	0.50	0.0749
C18	Clay	44.67	1.75	46.17	24.46	1.232	0.33	0.0880

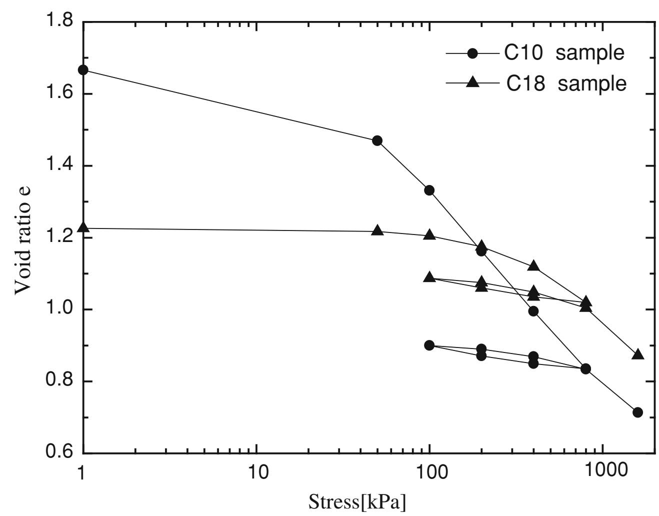

Fig. 2 The *e-lgp* curves for clay at different depth

facies and fluvial facies, indicating that it was formed in the process of marine transgression.

The laboratory tests were carried out on undisturbed samples to obtain reliable mechanical parameters for project design. Two different samplers have been used to procure the undisturbed samples from Jinzhou bay: the thin wall stationary piston and the fixed piston sampler. The thin wall stationary piston was used for the soft marine clay up to 12 m below seabed, while the fixed piston sampler for deeper soils. All the samples were immediately sealed on-site to maintain their native states and then carefully trimmed into specimens for testing. The general physical properties of these samples, as shown in Table 2, were also tested in laboratory.

3 Test Results

3.1 Conventional Consolidation Tests

Figure 2 presents the *e*-lg*p* curves obtained for clay at different depth below seabed by consolidation-rebound tests and the corresponding compression and swelling indexes were given in Table 2. It can be seen that the *e*-lg*p* curve for C10 sample is linear at normally consolidated state, while the curve for C18 sample is generally featured by global non-linearity. This observation indicates the stress dependent compressibility of C18 sample. The compression index for Dalian clay is found linearly related to their initial void ratio. Generally, the compression index can be estimated by the relation of $C_c = 0.283 \times (e_0 + 0.039)$.

3.2 One-Dimensional Creep Test Results

Figure 3 provides the variation of void ratio with elapsed time in terms of e-lgt curves. It can be seen that the compression curves for both samples are general in “S” shape as described in the text on soil mechanics, indicating the deformation of soil due to primary and secondary consolidation in the creep tests. Secondary consolidation is clearly observed in a rather long-term under a constant effective stress after primary consolidation. When the consolidation pressure is small, the secondary consolidation is hardly observed in three days after the application of load. When the stress is large enough, however, the deformation due to

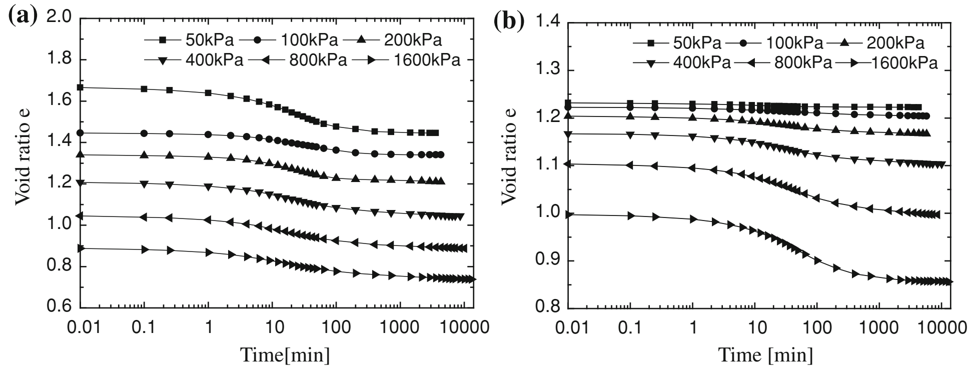

Fig. 3 The *e-lgt* curves obtained under one-dimensional conditions **a** C10 sample **b** C18 sample

secondary consolidation is still significant even 4 or 5 days after applying the consolidation pressure. It has been reported that secondary consolidation occurs with the soil structure adjustment at the particulate level (Jiang et al. 2009; Mesri and Castro 1987) and the diffusion of double layer (Fang et al. 2007). Both the processes are characterized by stress-dependent and time consuming. Hence the secondary consolidation often increases with the elapse of time and sustains much longer due to the increase of consolidation pressure.

In addition to the above-mentioned common features, some differences in the deformation of the marine clay are also worth mentioning here. It can observed that the strain induced by incremental stress at each loading stage for the upper marine remains the same more or less when the consolidation pressure becomes 200 kPa for C10 sample. The corresponding incremental strain for C18 sample, however, becomes larger and larger with increasing pressure.

The secondary consolidation coefficient defined by Eq. (1) was used to evaluate the creep property of Dalian clay.

$$C_\alpha = (e_1 - e_2)/\lg(t_2/t_1) \tag{1}$$

where t_1, t_2 are the time when creep deformation is observed and e_1, e_2 are the void ratio corresponding to t_1 and t_2.

Figure 4 presents the variation of secondary consolidation coefficients with increasing consolidation pressure. As shown in Fig. 4, a dramatic increase in the secondary consolidation coefficient can be observed when the consolidation pressure increases. The secondary consolidation coefficients for both samples eventually stabilized when consolidation pressure becomes larger enough. As mentioned above, creep property describing soil deformation at a constant effective stress connects with the particle rearrangement and structure alteration. The structure usually changes more significantly when the effective stress increases until the inherent structure has been totally damaged. Thus, the secondary consolidation coefficient of soil is observed increasing with effective stress when the soil is over-consolidated, and being almost steady at normally consolidated state (Shao, 2008).

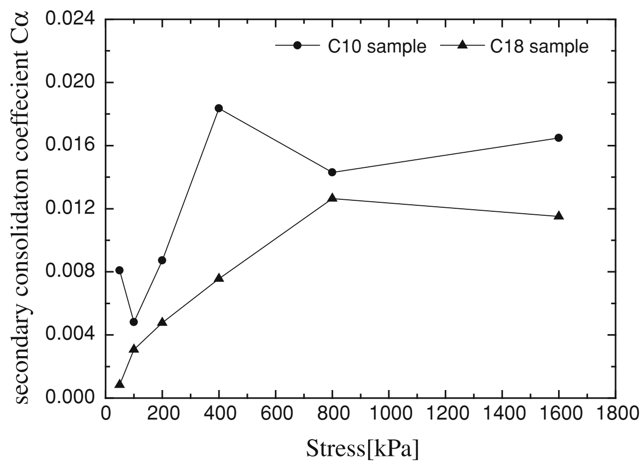

Fig. 4 Variation of secondary consolidation coefficient with effective stress

3.3 Triaxial Creep Tests

The observations of creep behaviors of Dalian marine clay obtained by triaxial creep tests under different confining pressures were quite similar, thus only the results from the confining pressure of 400 kPa are discussed here.

3.3.1 Time-Strain Curves

Fig. 5 presents the variation of axial strain with elapsed time for Dalian clay at different stress level. For both samples, the creep deformation increases greatly in a rather short run after the deviator stress was loaded, and in a fairly long run the creep develops at an attenuating rate which would becomes too small to contribute the deformation of soil. Consequently, the failure of soil was always observed in the loading period instead of the creep stage. This may be accounted for by soil deformation mechanism. Just like in one-dimensional creep tests, soil deformation in drained triaxial test also results from primary and secondary consolidation. The former relates to the drainage of pore water and the soil skeleton alteration due to increasing effective stress, while the latter relates to the further particle

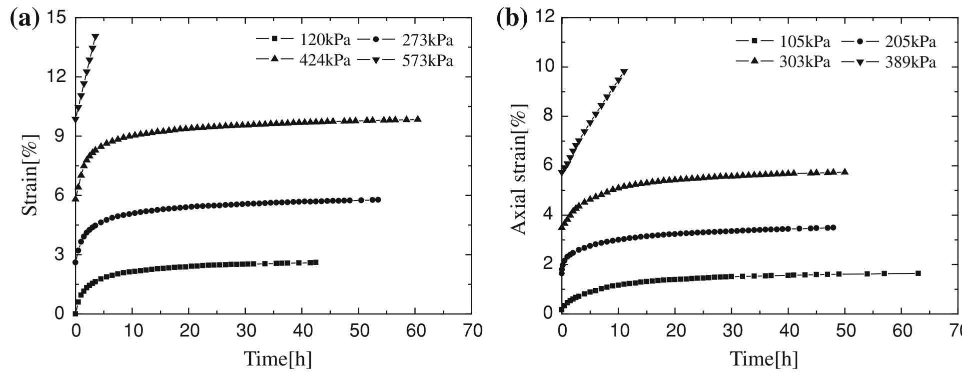

Fig. 5 Strain-time curves for Dalian clay **a** C10 sample **b** C18 sample

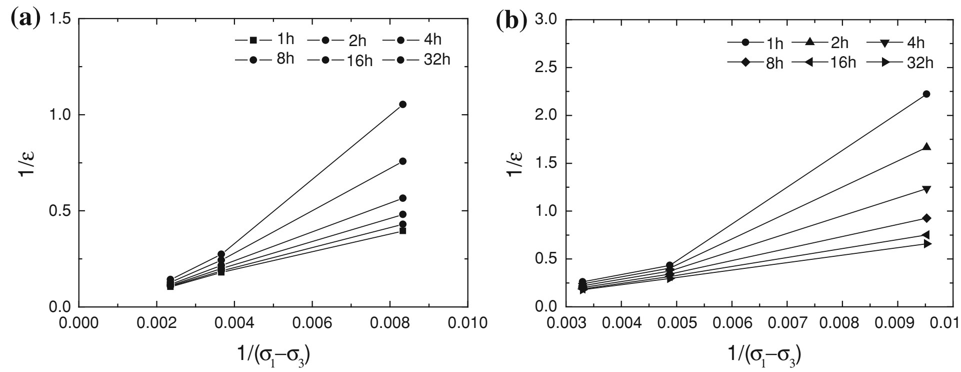

Fig. 6 Stress-strain relationship for typical Dalian clay **a** C10 sample **b** C18 sample

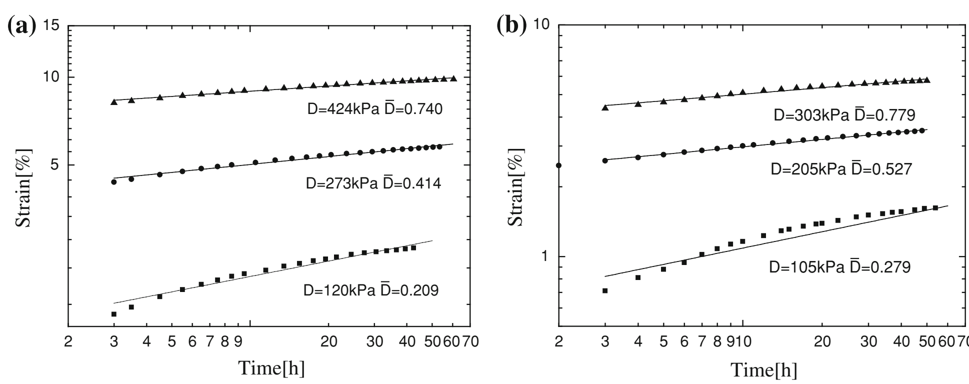

Fig. 7 Simulating curves of the Mesri creep model **a** C10 sample **b** C18 sample

rearrangement at a constant effective stress. Under drainage condition, soil particles arrange tighter and weak absorption layer turns thinner due to the drainage of pore water and the compression of soil skeleton in primary consolidation. These effects undoubtedly strengthen the soil structure and weaken the subsequent creep.

Note that, the soil creep deformation may develop fast after loading and then leads to soil failure, especially at high stress level, under undrained condition. In fact, foundation resting on soft clay may collapses due to accumulated creep under poor drainage condition. Thus, it had better to enhance the drainage capability of soil to prevent the creep induced failure.

4 Stress-Strain-Time Relationship and Model for the Soil

The stress-strain-time relationship was firstly raised by Singh and Mitchell (1968):

$$\varepsilon = Be^{\beta\bar{D}}\left(\frac{t}{t_1}\right)^{\lambda} \tag{2}$$

As mentioned above, Mesri described the stress-strain relationship using the hyperbolic equation proposed by Konder (1963). According to the hyperbolic equation, the stress-strain relationship can be expressed as:

Table 3 The parameters of Mesri creep model

No.	E_u/S_u	$\bar{D}$	R_f	λ	No.	E_u/S_u	$\bar{D}$	R_f	λ
C10	0.373	0.209	0.919	0.175	C18	1.134	0.270	0.926	0.234
	0.326	0.414	0.912	0.090		0.880	0.527	0.920	0.107
	0.587	0.74	0.915	0.059		1.356	0.779	0.919	0.094

$$\varepsilon/(\sigma_1 - \sigma_3) = a + b\varepsilon \tag{3}$$

Figure 6 presents some typical stress-strain isochrones for Dalian clay in cartesian coordinates with ordinate axis of $\varepsilon/(\sigma_1 - \sigma_3)$. It can be seen the linear relationships for these isochrones in the new coordinates. Hence, we develop the stress-strain-time relationship for Dalian clay using Mesri model here.

The initial tangential modulus E_{u} can be derived from Eq. (3) as,

$$E_{\mathrm{u}} = \left.\frac{d(\sigma_1 - \sigma_3)}{d\varepsilon}\right|_{\varepsilon=0} = \frac{1}{a} \tag{4}$$

The ultimate deviator stress $(\sigma_1 - \sigma_3)_f$ can be derived from Eq. (3) as,

$$(\sigma_1 - \sigma_3)_{ult} = \lim_{\varepsilon\to\infty} \frac{\varepsilon}{a + b\varepsilon} = \frac{1}{b} \tag{5}$$

It can be seen that $(\sigma_1 - \sigma_3)_{ult}$ is the deviator stress when the axial strain of specimen becomes infinite. Actually, the axial strain cannot be infinite and the soil usually fails at a certain strain of ε_f rather than the infinite strain. Here the failure stress ratio is used,

$$R_f = \frac{(\sigma_1 - \sigma_3)_f}{(\sigma_1 - \sigma_3)_{ult}} = \frac{(\sigma_1 - \sigma_3)_f}{1/b} \tag{6}$$

where $(\sigma_1 - \sigma_3)_f$ is the failure stress at the strain of ε_f.

Substitute Eqs. (4–6) into (3), and then the axial strain can be expressed as:

$$\varepsilon = \frac{(\sigma_1 - \sigma_3)_f}{E_u} \frac{\bar{D}}{1 - R_f\bar{D}} \tag{7}$$

where $\bar{D} = (\sigma_1 - \sigma_3)/(\sigma_1 - \sigma_3)_f$ is the stress level.

Thus, the Mesri model can be expressed as:

$$\varepsilon = \frac{2}{E_u/S_u} \frac{\bar{D}_1}{1 - (R_f)_1\bar{D}_1} \left(\frac{t}{t_1}\right)^{\lambda} \tag{8}$$

where $S_u = (\sigma_1 - \sigma_3)_f \big/ 2$.

So Eu/Su, Rf and λ are the parameters involved in Mesri creep model (Mesri et al. 1981).

Figure 7 provides the simulation results for Dalian clay by Mesri creep model and the parameters were given in Table 3.

It can be seen that when the strain does not increase with time in the initial period when the stress level is high or low, and thus there is some deviation between testing and simulation results. However, Mesri creep model can generally well describe the creep deformation of Dalian clay at most stress level. Thus, it can be used to estimate the long term settlement of foundation due to soil creep.

5 Conclusion

Foundation settlement is one of the major concerns in coastal reclamation project, especially the long term settlement due to soil creep. This paper investigated the compression behaviors of Dalian marine clay involved in an ongoing coastal reclamation project in Dalian, China. The main conclusion can be made as follows:

1. The *e*-lg*p* curves for Dalian marine clay could either be linear or nonlinear at normally consolidated state, indicating the stress dependency in compressibility of such a marine clay, which should be paid specific attention in the design.
2. Creep tests results show that the deformation of Dalian clay usually lasts in a fairly long run, especially under high stress level. Note that both one-dimensional and triaxial creep tests presented in this paper were performed under completely drainage condition, thus the soil hardly fails due to creep which is often observed in undrained condition.
3. Under one-dimensional condition, the secondary consolidation coefficient increases with effective stress when the soil is over-consolidated. The variation of the secondary consolidation coefficient can be nearly neglected at the normally consolidated state.
4. The creep of Dalian marine clay characterizes nonlinearity and can be expressed by hyperbolic equation. Thus the stress-strain-time relationship based on the Mesri creep model can well describe the time-dependent deformation of Dalian clay and be used to estimate the foundation settlement in the long run.

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