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Research paper

Experimental study of primary consolidation time for structured and destructured clays

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ABSTRACT

Incremental load one-dimensional consolidation tests were performed on undisturbed and reconstituted specimens of seven natural clays with a predominant clay mineral of illite. Both the settlement and the base pore pressure under step load increments were measured during the dissipation of pore pressure. The change law in the primary consolidation time determined by the pore pressure dissipation with increasing stress level is found to be contrary to that determined by the Taylor method and the Casagrande method which are often used in laboratory tests and engineering practice. The primary consolidation time determined based on the time-dependent settlement observations is smaller than that determined by the pore pressure dissipation for the natural clays investigated. Pore pressure is generally not completely dissipated at the primary consolidation time determined by the Taylor method and the Casagrande method. Such remaining pore pressure may reach a quite high percentage of the step load increment for the investigated specimens. The settlement determined by the Taylor method and the Casagrande method may be significantly underestimated due to the dissipation of remaining pore pressure. Attention should be paid to the possible distortion on consolidation behavior in laboratory tests and engineering practice due to the remaining pore pressure and the associated settlement.

1. Introduction

Incremental load one-dimensional consolidation tests are often performed to study the consolidation behavior of both the undisturbed and the reconstituted specimens of natural clays (e.g., Liu and Carter, 1999, 2000; Alawaji, 1999; Horpibulsuk et al., 2007; Liu et al., 2013). Note that reconstituted clays are often used as destructured clays to compare with undisturbed specimens of natural clays as structured clays for assessing the effects of soil structure developed during the depositional and post-depositional processes (e.g., Burland, 1990; Liu and Carter, 1999, 2000). The determination of the end of primary consolidation (EOP) is essential for the incremental load consolidation tests, and the time-settlement readings are required on all load increments for reaching 100% primary consolidation (e.g., American Society for Testing and Materials, 1989; Head, 1992). Many important consolidation parameters are significantly affected by the primary consolidation time, such as the analysis of hydraulic conductivity during compression (e.g., Tavenas et al., 1983; Berilgen et al., 2006; Dolinar, 2009; Horpibulsuk et al., 2011; Zeng et al., 2011); the coefficient of consolidation associated with deformation analysis and settlement rate estimation (e.g., Parkin, 1978; Sridharan et al., 1995; Mesri et al., 1999; Cortellazzo, 2002; Gurtug, 2011), the secondary consolidation (e.g., AL-Zoubi, 2010; Deng et al., 2012) and so on.

According to the Terzaghi effective stress principle, primary consolidation refers to the time-dependent compression process associated with the dissipation of pore pressure. Note that pore pressure is not commonly measured in incremental load one-dimensional consolidation tests. Most previous studies on the determination of the consolidation time at EOP were carried out based on the settlement–time curves obtained from incremental load one-dimensional consolidation tests without measuring pore pressure. The Taylor method (the square root of time-fitting method) and the Casagrande method (the logarithm of time-fitting method) are the most notable methods for determining the EOP in engineering practice (e.g., Olson, 1986; Robinson and Allam, 1996). These fitting methods with settlement–time curves are established based on the Terzaghi one-dimensional consolidation theory.

Note that Tavenas et al. (1983) concluded that the use of the Terzaghi one-dimensional consolidation theory to interpret the results of incremental load consolidation tests in terms of the coefficient of consolidation and the hydraulic conductivity is highly questionable. Hence, it is logically deduced that the consolidation time at the EOP determined based on the Terzaghi one-dimensional consolidation theory may be significantly different from that determined based on the pore pressure

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Abbreviations: EOP, End of primary consolidation; LIR, Load incremental ratio; R, Reconstituted specimens; U, Undisturbed specimens; XRD, X-ray diffractometry.

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Notation

D_{stpc}	degree of additional settlement induced by remaining pore pressures at t_{pc} (defined as $(\Delta s_{tpu} - \Delta s_{tpc}) / \Delta s_{tpu} \times 100\%$)
D_{stpt}	degree of additional settlement induced by remaining pore pressures at t_{pt} (defined as $(\Delta s_{tpu} - \Delta s_{tpt}) / \Delta s_{tpu} \times 100\%$)
D_{utpc}	degree of remaining pore pressure at t_{pc} (defined as $u_{btpc} / \Delta\sigma'_v \times 100\%$)
D_{utpt}	degree of remaining pore pressure at t_{pt} (defined as $u_{btpt}/\Delta\sigma'_v \times 100\%$)
d_0	corrected zero compression point in the Taylor method
d_{90}	90% primary compression point in the Taylor method
d_{100}	100% primary compression point in the Taylor method
e	void ratio at the end of pore pressure dissipation under a given σ'_v
PI	plasticity index
t	elapsed time
t_{pc}	primary consolidation time determined by the Casagrande method
t_{pt}	primary consolidation time determined by the Taylor method
t_{pu}	primary consolidation time determined by pore pressure dissipation
t_{pu20}	t_{pu} for 20 mm − height specimens
t_{pu40}	t_{pu} for 40 mm − height specimens
w_L	liquid limit
w_n	natural water content
w_P	plastic limit
w_0	initial water content
u_b	base pore pressure measured at the base of specimen
u_{bmax}	maximum value of base pore pressure
u_{br}	residual base pore water pressure at $du_b/dt = 0$
u_{btpc}	base pore pressure measured at t_{pc}
u_{btpt}	base pore pressure measured at t_{pt}
σ'_v	vertical effective stress
σ'_{vy}	consolidation yield stress of undisturbed specimens
σ'_{yr}	remolded yield stresses of reconstituted specimens
Δs_{tpc}	settlement at t_{pc}
Δs_{tpt}	settlement at t_{pt}
Δs_{tpu}	settlement at t_{pu}
$\Delta\sigma'_v$	step load increment

dissipation associated with the Terzaghi effective stress principle. The experimental comparisons of primary consolidation time determined using the settlement measurements and the pore pressure dissipation have been seldom carried out in the previous studies.

This study aims at investigating the difference in consolidation time at the end of primary consolidation determined by the pore pressure dissipation and that determined based on the settlement–time curves (the Casagrande method and the Taylor method). Toward this end, incremental load one-dimensional consolidation tests were performed on 14 specimens of 7 types of natural clays. The mineralogical compositions of the clays investigated were identified by X-ray diffractometry tests. The changing trends of primary consolidation time determined by both the pore pressure and the settlement observations with vertical effective stress are firstly investigated based on the test results. Then, the primary consolidation time determined by the dissipation of pore pressure is compared with that determined by the Taylor method and the Casagrande method. Finally, the possible distortions on the consolidation behavior with the Taylor method and the Casagrande method are discussed.

2. Materials and clay mineralogy

The basic physical properties of the investigated clays are shown in Table 1. The liquid limits (w_L) measured using the Casagrande method (BS1377: Part 2: 1990: 4.3) change from 43.8% to 100.0%. The plastic limits (w_P) were determined in accordance with BS1377: Part2: 1990: 5.3, as suggested by Head (1992). Fig. 1 shows the plasticity chart, indicating that all the clays lie slightly above or on the A-line defined by $PI = 0.73(w_L - 20)$, but below the U-line defined by $PI = 0.9(w_L - 8)$, where PI is the plasticity index. Note that Zeng et al. (2011) analyzed the hydraulic conductivity during compression with Nanjing clay #7, Nanjing clay #9, Lianyungang clay #4, and Lianyungang clay #12. These clays are designated in this study as Nanjing clay A, Nanjing clay B, Lianyungang clay B and Lianyungang clay C, respectively. The reconstituted specimens of Huaian clay A, Huaian clay B and Lianyungang clay A were used by Zeng et al. (2015) for identifying the change pattern of settlement–time curves during primary consolidation. In this study, the experimental data of both the pore pressure and the settlement observations from the tests on 6 undisturbed and 8 reconstituted specimens of 7 clays in Table 1 are analyzed for investigating the difference in consolidation time at the EOP determined based on the settlement–time curves and the pore pressure dissipations. The symbol U and R represent the undisturbed and the reconstituted specimens respectively. The numbers after U and R represent the initial heights of specimens for tests, being 20 mm and 40 mm respectively.

All the specimens had a diameter of 61.8 mm, the same as the conventional consolidation cell commonly used in China. The standard consolidation cell with a height of 20 mm generally has a ratio of diameter to height being about 2.5 for minimizing the friction effect on the specimen when loaded. Note that several researchers reported that large strain occurs for the reconstituted specimens with high initial water contents when loaded under low stress levels (e.g., Hong et al., 2010; Bo et al., 2015). The friction effect can be also expected to be not significant at low step loads. In addition, Hong et al. (2013) proposed a method of preparing the specimens for consolidated undrained triaxial compression shear tests using a large-diameter oedometric apparatus with a height of 150 mm and a diameter of 283 mm, and illustrated that the compression curves obtained from the large-diameter oedometric apparatus were almost identical to those obtained from a standard cell with a height of 20 mm and a diameter of 61.8 mm. Hence, a modified cell with a height of 40 mm and a diameter of 61.8 mm can be considered to be satisfactory for the specimens with high initial water contents when loaded beginning from a very low effective stress. Note that for all the specimens investigated, the ring was smeared with silicone grease to minimize the side friction.

Single drainage was allowed on the top of the specimen during consolidation. The bottom porous stone was connected to a pore pressure transducer for measuring the base pore pressure (u_b) at the base of specimen. For reconstituted clays with initial water contents (w_0) being larger than the liquid limits, a modified one-dimensional consolidation apparatus starting from a low vertical effective stress (σ'_v) of 0.5 kPa is adopted for avoiding the problem of soil squeezing through clearance between the confining ring and upper porous disc as addressed by Head (1992). The modified apparatus is equipped with a light loading cap and two weight hanger systems. The first hanger is under the center point of the consolidation cell, and the second one is the same as for a standard oedometer test rig. When the required vertical stress is less than 12.5 kPa, the second weight hanger used in the standard oedometer test rig is removed. More details can be found in Hong et al. (2010). The loading steps (σ'_v) for the reconstituted specimens of Huaian clay A, Huaian clay B and Lianyungang clay A were 0.5 kPa, 1.5 kPa, 2.5 kPa, 4.5 kPa, 8.5 kPa, 12.5 kPa, 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa and 1600 kPa. Before σ'_v reaches 12.5 kPa, the load incremental ratio (LIR) defined by $\Delta\sigma'_v/\sigma'_v$ changes within the range of 0.5 to 2.0. When $\sigma'_v > 12.5$ kPa the LIR becomes unity. The effect of LIR on consolidation behavior is not considered for