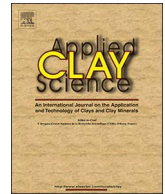




Contents lists available at ScienceDirect

Applied Clay Science

journal homepage: [www.elsevier.com/locate/clay](http://www.elsevier.com/locate/clay)

Research paper

# Experimental investigations on discrepancy in consolidation degrees with deformation and pore pressure variations of natural clays

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## ARTICLE INFO

## Keywords:

Clays  
Clay minerals  
Theoretical line  
Experimental relationships  
Deformation-time curve  
Excess pore pressure dissipation

## ABSTRACT

Degrees of consolidation can be determined by two different methods using deformation and excess pore pressure variations for reconstituted and natural clays in laboratory tests and engineering practice. Theoretically, the relationship between the degrees of consolidation determined using the two methods should be unique. However, this study finds the experimental results from fifteen one-dimensional incremental load consolidation tests on five kinds of natural clays deviated from the theoretical line. The experimental relationships correlating the degrees of consolidation determined by the two methods are also found not unique, instead, consisting of a cluster of curves depending on different step stress increments. Two key causes are found to be responsible for the substantial discrepancy between experimental and theoretical results: (1) the nonlinear development of deformation during the dissipation of excess pore pressure; (2) the degree of consolidation determined by excess pore pressure measurements lower than 100% when the degree of consolidation determined based on the deformation-time curve becomes 100%. It is also found that the experimental relationships correlating the degrees of consolidation determined by the two methods are significantly affected by the values of degree of consolidation with excess pore pressure dissipation at 100% of consolidation degree with deformation observations.

## 1. Introduction

Degree of consolidation (DOC) is one of the most important parameters in laboratory tests and engineering practice. For example, it is an essential parameter in determining the end of primary consolidation in conventional practice (e.g., Head, 1992; Deng et al., 2012; Cui et al., 2013; Liu et al., 2013; Han, 2015), consequently relating to compression curves for both reconstituted and natural clays (e.g., Terzaghi et al., 1996; Zeng et al., 2016) and soil structure evaluation (e.g., Liu and Carter, 1999, 2000). It is also closely related to the coefficient of consolidation of clays associated with deformation analysis and settlement rate estimation (e.g., Sridharan et al., 1995; Mesri et al., 1999; Horpibulsuk et al., 2011; Wang et al., 2013). It is a key design parameter for ground improvement and the disposal of reclaimed land filled by dredged clays under surcharge or vacuum preloading (e.g., Chu

et al., 2000; Zhang et al., 2015; Wang et al., 2016) and so on.

Note that DOC can be determined with two different methods in terms of the increase of vertical deformation and the dissipation of excess pore pressure (e.g., Terzaghi et al., 1996; Robinson, 2003). It has been theoretically recognized that the DOC determined by a deformation-time curve should have a unique relationship with that determined by the dissipation of excess pore pressure (e.g., Crawford, 1964; Robinson, 1999, 2003). Note that some researchers found that the values of DOC determined by the two different methods deviated from the theoretical line based on field observations from embankment construction (e.g., Wu et al., 2015; Zhang et al., 2015), long-term settlement behaviour of metro tunnels (Shen et al., 2014; Wu et al., 2017) and groundwater pumping (Shen and Xu, 2011; Shen et al., 2013; Wu et al., 2016).

The objectives of this study are (1) to understand the conditions of

*Abbreviation:*  $d_{fc}$ , Deformation at 100% of degree of consolidation determined by the Casagrande method;  $d_{fu}$ , Deformation at the end of excess pore pressure dissipation; *DOC*, Degree of consolidation;  $d_e$ , Deformation at elapsed time; prefix *R*-, Reconstituted specimen; prefix *U*-, Undisturbed specimen;  $w_L$ , Liquid limit;  $w_n$ , Natural water content;  $w_p$ , Plastic limit;  $w_0$ , Initial water content;  $u_b$ , Excess pore pressure measured at the base of specimen;  $u_{bmax}$ , Maximum value of excess pore pressure;  $u_{br}$ , Residual excess pore pressure at the base of specimen at  $du_b/dt = 0$ ;  $u_{bt}$ , Excess pore pressure at elapsed time measured at the base of specimen;  $U_{set}$ , Degree of consolidation determined from deformation-time curve;  $U_{sc}$ , Degree of consolidation defined by the Casagrande method;  $u_e$ , Excess pore pressure at elapsed time;  $U_{in}$ , Degree of consolidation determined from excess pore pressure dissipation;  $U_{ub}$ , Degree of consolidation determined from excess pore pressure at the base of specimen;  $U_{ubc}$ , Degree of consolidation determined by excess pore pressure dissipation at  $d_{fc}$ ;  $t$ , Elapsed time;  $T_v$ , Time factor; *XRD*, X-ray diffractometry;  $\sigma_v$ , Step load;  $\sigma'_v$ , Effective vertical stress;  $\Delta d_v$ , Increment of deformation;  $\Delta U_{set}$ , Increment of  $U_{set}$ ;  $\Delta U_{ub}$ , Increment of  $U_{ub}$ ;  $\Delta \sigma_v$ , Step stress increment

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supporting the theoretical line, (2) to investigate the experimental relationships correlating DOCs determined by the two different methods, and (3) to study the key factors of influencing the experimental relationships between DOCs determined by the two different methods. Towards the above purposes, the deformation-time curves and the data of excess pore pressure dissipation from fifteen types of one-dimensional incremental load consolidation tests for undisturbed and reconstituted specimens of five kinds of natural clays are analyzed, and the experimental results are compared with the theoretical line.

## 2. Theoretical line of degrees of consolidation by two methods

Based on the Terzaghi effective stress principle, the degree of consolidation ( $U_u$ ) determined from the dissipation of excess pore pressure can be expressed as:

$$U_u (\%) = (\Delta\sigma_v - u_t) / \Delta\sigma_v \times 100\% \quad (1)$$

where  $\Delta\sigma_v$  is the step stress increment and  $u_t$  is the excess pore pressure at elapsed time ( $t$ ) under the step stress increment. On the other hand, the degree of consolidation ( $U_{se}$ ) determined by the deformation-time curves can be defined as:

$$U_{se} (\%) = d_t / d_{fu} \times 100\% \quad (2)$$

where  $d_t$  is the deformation increment at the elapsed time ( $t$ ) and  $d_{fu}$  is the deformation at the end of excess pore pressure dissipation under the given value of  $\Delta\sigma_v$ .

When excess pore pressure is measured at the base of specimen, Eq. (1) can be rewritten as:

$$U_{ub} (\%) = (\Delta\sigma_v - u_{bt}) / \Delta\sigma_v \times 100\% \quad (3)$$

where  $U_{ub}$  is the degree of consolidation at the specimen base and  $u_{bt}$  is the excess pore pressure at elapsed time ( $t$ ) measured at the specimen base. Note that  $U_{se}$  is the average degree of consolidation of a consolidating layer;  $U_{ub}$  is defined at the location of the specimen base.

According to the Terzaghi one-dimensional consolidation theory (Terzaghi et al., 1996), the theoretical relationship correlating the DOCs determined by the two different methods based on the measurements of deformation development and excess pore pressure dissipation should be unique. The equations for  $U_{se}$  and  $U_{ub}$  can be expressed as follows (Robinson, 2003):

$$U_{se} = U_u = 1 - \sum_{m=0}^{m=\infty} \frac{2}{M^2} \exp(-M^2 T_v) \quad (4)$$

$$U_{ub} = 1 - \sum_{m=0}^{m=\infty} \frac{2}{M} \sin M \exp(-M^2 T_v) \quad (5)$$

where  $M = (2m + 1)\pi/2$  and  $T_v$  is time factor. A theoretically unique line of  $U_{se}$  versus  $U_{ub}$  can be obtained with Eqs. (4) and (5), as shown in Fig. 1. It can be seen that when  $U_{ub} > 35\%$ , the value of  $U_{se}$  increases linearly with the increase in  $U_{ub}$ . The slope of the linear line defined by  $\Delta U_{se} / \Delta U_{ub}$  is found to be 0.64. The term  $\Delta U_{se}$  is the increment of  $U_{se}$  and  $\Delta U_{ub}$  represents the increment of  $U_{ub}$ . Hence, the following equation can be obtained:

$$\Delta U_{se} = 0.64 \Delta U_{ub}, \text{ when } U_{ub} > 35\% \quad (6)$$

Note that Robinson (2003) suggested the linear relationship when  $U_{ub} > 22\%$ . Careful investigation indicates that slightly nonlinear  $U_{se} - U_{ub}$  relationship can be found between  $U_{ub} = 22\% - 35\%$  and its slope changes from 0.69 to 0.64.

## 3. Experimental observations

### 3.1. Materials and mineralogical compositions

For testing the theoretical results with experimental observations, five kinds of natural clays were used, as shown in Table 1. The prefix  $R$ -

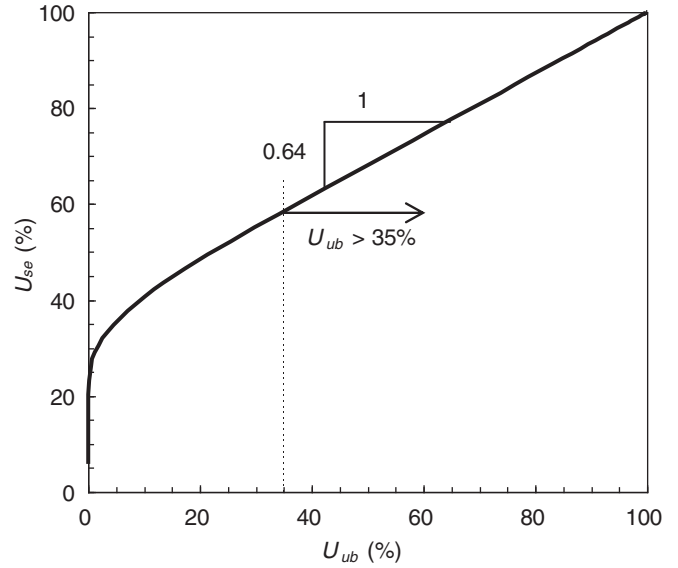


Fig. 1. Theoretical line between  $U_{se}$  and  $U_{ub}$ .

before the clay name presents the reconstituted specimen, and the prefix  $U$ - refers the undisturbed specimen. The values of liquid limit ( $w_L$ ) and plastic limit ( $w_p$ ) were measured using the Casagrande apparatus method and the rolling method respectively, as described in Head (1992). The values of  $w_L$  for the five kinds of clays vary within a wide spectrum ranging from 43.8% to 100.0%.

X-ray diffractometry (XRD) tests were carried out on air-dried specimens of field-moist samples for the five kinds of clays except for Huaian clay B. Their random powder diffractions are shown in Fig. 2. It can be seen that the main nonclay minerals are quartz, feldspar and calcite. The main clay minerals can be also found as kaolinite, illite and chlorite. In addition, the basal order reflections = 12–15 Å may be responsible for smectite/vermiculite/chlorite. Mitchell and Soga (2005) pointed out that smectite expands to 17 Å after treatment with ethylene glycol.

The quantities of clay minerals can be approximately determined from XRD tests results on the clay fractions ( $< 2 \mu\text{m}$ ). Zeng et al. (2011) and Zeng and Hong (2015) investigated the clay minerals of the clays in Table 1. The XRD testing specimens were prepared following the methods described in Whittig and Allardice (1986). Field-moist samples were reacted with 6%  $\text{H}_2\text{O}_2$  to remove organic matters and were dispersed by 4%  $(\text{NaPO}_3)_6$ . Then, the clay fractions ( $< 2 \mu\text{m}$ ) were collected by repeated centrifuging. Afterwards, 1 mL water was added. An aliquot of the dispersion containing about 30 mg clay was dropped onto a glass slide.

Main clay minerals of clays can be identified based on the basal order reflections of X-ray diffraction patterns, and detail information refers to Zeng et al. (2011) and Zeng and Hong (2015). Then, the quantity of clay minerals was determined with a semi-quantitative method by comparing the reflection areas, following Mitchell and Soga (2005). Table 2 shows the compositions of clay minerals for the five kinds of clays. It can be seen that the predominant clay mineral is illite, with a proportion varying within the range of 59% to 68%.

### 3.2. Consolidation tests

Fifteen types of one-dimensional incremental load consolidation tests were carried out on undisturbed and reconstituted specimens of five kinds of natural clays. Note that the specimens of Huaian clay A, Huaian clay B and Lianyungang clay were reconstituted at different initial water contents ( $w_0$ ) with a spectrum of  $w_0/w_L = 0.8 - 1.8$  with most being larger than 1.0. In such cases, adequate attention should be

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