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Mechanisms of quasi-preconsolidation stress development in clays: A rheological model

Boning Ma[a], Balasingam Muhunthan[b,*], Xinyu Xie[c]

[a]School of Civil and Transportation Engineering, Beijing University of Civil Engineering and Architecture, Beijing, China
[b]Department of Civil and Environmental Engineering, Washington State University, Pullman, WA, USA
[c]Ningbo Institute of Technology, Zhejiang University, Ningbo, Zhejiang, China

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Abstract

This paper deals with the development of a mechanistic model for the ageing consolidation behavior of clays with the focus on aspects related to the development of quasi-preconsolidation pressure. The initial use of such pressure in design met with criticism, but field and laboratory evidence, which highlights its significance, continues to accumulate. A nonlinear rheological model is used to numerically simulate the consolidation process of clay in laboratory tests and to identify the basic mechanical parameters that contribute to the development of the quasi-preconsolidation phenomenon. Methods to identify the parameters of the model from oedometer tests are described. It is shown that while the variation in soil modulus can be characterized by a linear form in the virgin compression region, it is nonlinear in the recompression region and is best characterized by a hyperbolic function. Changes to the modulus in the recompression region, due to ageing, is shown to be the dominant cause of the development of the quasi-p_c phenomenon. Observed results as well as numerical simulations demonstrate that specimens that had aged longer show increased quasi-p_c values. While the variation in soil modulus controls the EOP curve of clays, the observed time effects, such as the “vanishing p_c” phenomenon, are controlled primarily by changes in soil viscosity. However, this has no bearing on the development of the quasi-p_c phenomenon.

Keywords: Ageing; Soil rheology; Consolidation; Creep; Viscosity; Yield stress; Quasi-preconsolidation pressure

1. Introduction

Arthur Casagrande recognized that the reloading compressibility of a soil is much smaller than its virgin compressibility until the current effective overburden stress has exceeded a certain stress level. The 1-D consolidation curves presented in his seminal paper (Casagrande, 1932), as well as subsequent data, show that soil compressibility diminishes progressively until an abrupt change or yield occurs and this stress is exceeded. The yield stress is generally defined as the *preconsolidation pressure* (p_c), and the methodology proposed by Casagrande (1936) to determine it, based on laboratory consolidation tests, has been widely used by geotechnical engineers to calculate consolidation settlements in clays. Variations of this methodology have been proposed by a number of investigators (see a summary in Mitchell and Soga, 2005).

Significant differences between the observed and the predicted settlements of clays, using the pressure determined from the Casagrande methodology, prompted Gerald A. Leonards of

*Corresponding author. Tel.: +1 509 335 9578; fax: +1 509 335 7632.
E-mail address: muhuntha@wsu.edu (B. Muhunthan).
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Nomenclature

c_v	coefficient of consolidation in the normal consolidation stage
h_c	depth of the moving boundary
k_v	coefficient of vertical permeability
m_v	coefficient of volume compressibility
q	loading pressure
t	time
u	excess pore water pressure
u_a	average excess pore water pressure
z	depth
H_{dr}	length of drainage
E_0	modulus of the spring in the Maxwell body
E_1	modulus of the spring in the Kelvin body
E_s	modulus of soil compressibility
T_v	time factor
U	degree of consolidation
ε_z	vertical strain
γ_w	unit weight of water
η_0	coefficient of viscosity of the Maxwell body
η_1	coefficient of viscosity of the Kelvin body
σ_z'	vertical effective stress
p	consolidation pressure (total vertical stress)
p_c	preconsolidation pressure
p_{cq}	quasi-preconsolidation pressure

Purdue University to initiate a systematic program using remolded, artificially sedimented, and field clay samples to identify factors other than the maximum past effective stress state that could affect the value of p_c. The results of this program (Raju, 1956; Leonards and Ramiah, 1959; Leonards and Altschaeffl, 1964) showed that the yield stress could exceed p_c significantly due to many factors, including thixotropy and volumetric creep. The increased yield stress due to such effects was termed by Leonards as the *quasi-preconsolidation pressure*, p_{cq}. Based on a suite of laboratory results, he used the ratio of $p_{cq}/p_c \approx 1.4$ to make "class A" predictions of the consolidation settlements of seven buildings in the town of Drammen, Norway (Leonards, 1968). The extraordinary match between the observed and the predicted settlements of these buildings enabled him to consistently use p_{cq} in geotechnical practice with great success (Leonards, 1977, 1980).

Bjerrum (1967, 1972) developed hypotheses to explain the quasi-preconsolidation phenomenon, but showed that the p_{cq} would actually vanish at field rates of strain. Since then, his *isotache* concept has drawn considerable attention and it is widely adopted by researchers to date (Watabe et al., 2012; Tsutsumi and Tanaka, 2012).

More recent studies, however, have begun to shed new light onto the generally beneficial effects of the ageing of soils and onto the preconsolidation phenomenon in particular and the factors that influence such effects (Mitchell and Soga, 2005). In the 25th Terzaghi Lecture, Schmertmann (1991) reported experimental results which show that the apparent OCR (ratio of the apparent preconsolidation pressure to the current pressure) of Italian clay equaled 1.5 to 2.0 after creep and, more importantly, even dry Florida quartz sand showed the development of similar effects. Schmertmann termed this phenomenon ageing preconsolidation. The establishment of a functional relationship between the time-effective stress and the apparent overconsolidation rate of artificially sedimented kaolinite clay was the focus of a study by Athanasopoulos (1993). Such a relationship would enable the prediction of the long-term behavior of soils from short-duration tests.

The mechanisms of the existence of an apparent preconsolidation pressure and an ageing phenomenon in clays and sands have been put forward by a number of investigators. Leonards and Deschamps (1995) presented a summary of such mechanisms and listed the following as contributing factors: (a) alteration clay minerals, (b) ions in pore water due to changes in concentration and/or valence, (c) precipitation/cementation, (d) mineral leaching/internal erosion, and (e) combination of time/volumetric strains at a constant effective stress. While circumstances may dictate some of these factors to be of greater consequence than others, Leonards hypothesized (e) to be the dominant mechanism in the development of the quasi-preconsolidation pressure.

Baxter and Mitchell (2004) presented the results of a systematic laboratory testing program to study the influence of above factors (a) to (e) on the presence and magnitude of the ageing effects in sands. Their results suggest that while the influence of most ageing factors of natural deposits can be identified in small-scale laboratory tests, the time-dependency may not be replicated (see also Seng and Tanaka, 2012) Soil particles mainly rearrange during the primary compression process. However, the increased time due to ageing enables the formation of new bonds between particles, this results in an altogether different behavior. These bonds may be mechanical (Schmertmann, 1991), chemical, or biological (Bolton, 2010) depending on the type of soils and stress histories. Such effects on consolidation are well documented and analyzed (Nakai et al., 2011; Deng et al., 2012.

The above discussion suggests that despite abundant field and laboratory evidence on the beneficial effects of ageing in soils, their use in practice has been hampered due to the lack of a comprehensive mechanistic model that can explain the different phenomena with clarity. This study uses a rheological model of the consolidation process in laboratory tests to identify the basic mechanical parameters that contribute to the development of the quasi-preconsolidation phenomenon in clays.

2. Features of quasi-preconsolidation pressure in clays

While a great deal of recent laboratory and field evidence exists, there is nothing more eloquent in setting the features of quasi-preconsolidation than the set of classical experimental