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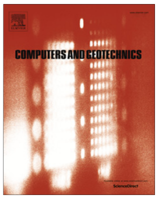

Research Paper

Numerical study of slurry consolidometer tests taking into account the influence of wall friction

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ABSTRACT

Three tests of slurried Jeeropilly coal tailings in a purpose-built slurry consolidometer under three different loading sequences were numerically analysed to study the friction losses quantitatively. A simplified sedimentation-consolidation theory was proposed to link the initial suspended state and soil-like state of slurries. The numerical simulations provided good agreement with the measured, and indicated the noticeable friction losses, from 11.1% to 34.2%, due to factors such as the diameter of consolidometers and loading sequences. The average coefficient of the stress (pore water pressure) stood at 1 at the beginning, and declined to a stable value around 0.55 (0.67).

1. Introduction

Slurries, such as dredging residues and mine tailings, undergo large settlement due to sedimentation and consolidation, which are required to be predicted [1–3]. This has prompted extensive experimental and theoretical studies of the problem over many decades [4–8].

Conventionally, the behaviour of slurries between the settling and the consolidation stage cannot be captured since they were studied in separate apparatus. These processes can be tested together in a slurry consolidometer which allows slurry to settle before consolidating under various loading sequences. However, comparing to conventional samples with maximum height-diameter ratio of approximately 2.5 [9], piston and wall friction in the slurry consolidometer is significant once the slurry develops effective stress, which complicates the interpretation and analysis of the results. Wickland & Wilson estimated in their large column tests that wall effects reduce vertical applied stresses by as much as 10–25% and could increase derived values of coefficient of volume change (m_v) and k by approximately 10–30%, based on a smooth-walled cell [10]. In order to determine the wall friction effects quantitatively, this paper considers the simulation of slurry consolidation test results using the finite element method.

2. Previous studies of sedimentation and consolidation

Conventional consolidometers such as the Rowe cells are usually of limited height (30 mm or 50 mm). However, to capture both the settling and consolidation behaviour, consolidometers need to accommodate relatively higher samples. A number of columns have been designed to study the settling and self-weight consolidation behaviour of a range of slurries, with no additional loading applied. Columns ranging in diameter from 47 to 1000 mm, and in height from 114 to 6000 mm, have been used [7,11–13,10]. There has been some further developments of columns, including accurately testing slurries of low densities and under low stresses [14]. Furthermore, the study of consolidation requires additional loadings on samples. Owen (1970) used a large consolidometer to study the consolidation of mud [15]. Bo et al. (1999) used a consolidometer measuring 495 mm in diameter and 1000 mm in height to study the deformation behaviour of slurry-like soil subjected to additional loading [16], whereas pore water in samples was drained radially due to the large diameter of the cell. Wong et al. (2008) conducted tests on fine-grained and non-segregation tailings in a consolidometer measuring 150 mm in diameter and 300 mm in height [17], but this consolidometer can only apply an additional load up to 20 kPa, which is insufficient for studying slurries consolidation behaviour. In order to overcome these problems, Shokouhi & Williams (2015) developed a slurry consolidometer measuring 150 mm in diameter and 410 mm in height, capable of applying

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a vertical stress of up to 500 kPa, to conduct tests on coal tailings slurry under a variety of loading sequences [18,19].

In slurry consolidometers, an aqueous slurry at an initial moisture content of well above its liquid limit is used to prepare a sample in suspension. This is of practical importance to understand the transition between the slurry state in which no particle-particle contact built, and the soil state in which particle-particle contact gives rise to effective stresses. Monte & Krizek tested a kaolinite clay slurry with an initial gravimetric moisture content of about 250% (approximately four or five times the liquid limit) and the void ratio at which effective stresses began was believed to be 7 [20]. Bo tested slurries with the void ratio in range of 2.1–2.68 [16,21]. De Oliveira-Filho and van Zyl [22]suggested that sedimentation of silt-sized soil ceases at a void ratio of 2.20, while Bartholomeeusen et al. suggested that the sedimentation of silt-sized river sediment ceases at void ratios between 2.09 and 4.48 [23]. Bonin et al. suggested a lower limiting void ratio than that suggested by both these authors [1]. Bo et al. suggested that the transition between a slurry and a soil can be determined from the void ratio at the peak pore pressure [24].

Apart from experimental studies, a number of techniques for the combined analysis of sedimentation and consolidation have been proposed. Been & Sills modified the linear solution of Gibson's equation in the light of observed experimental features to predict laboratory consolidation [7]. Pane & Schiffman linked pelagic sedimentation and consolidation as a single process governed by a modified effective stress equation, but detailed numerical solutions and laboratory verifications were not reported [8]. Toorman proposed semi-empirical relationships to form new closure equations of the unifying theory for sedimentation and self-weight consolidation [25]. Jeeravipoolvarn implemented a specific continuous interaction function to couple sedimentation and consolidation phenomena and examined the resulted model [3]. The represented effective stress-void ratio relationship in transition zone was further simplified in this paper. Bo proposed three compression indices for stresses covering three log cycles for ultra-soft soil to predict the magnitude and rate of settlement [26]. However, the influence of wall friction on parameters assessment is still unclear, which impedes these theories from reaching a better approximation of reality.

Some rough estimations on the influence of wall friction in slurry consolidometers were reported in the literature. Bo et al. estimated that friction on the side of the loading piston and on the wall reduced the stress applied to the slurry by 100–105 kPa on average [16]. Wong concluded that the effect of wall friction were difficult to quantify [17]. Umehara [27,11] and Shokouhi & Williams [18,19] reported on stress transducers mounted in the base plate and top cap to provide an estimate of the overall wall friction. Wickland et al. estimated wall friction in large-scale column tests on mixtures of mine waste rock and tailings to be 10–25% of the applied vertical stress [10]. In this paper, the finite element method has been used to study the influence of wall friction based on the results of large-strain consolidation tests under various loading sequences.

3. Wall friction in the purpose-built slurry consolidometer

As shown in Fig. 1, the slurry consolidometer was built by Wille-Geotechnik of Germany based on the specifications defined by The University of Queensland [18]. It consists of a stainless steel cell of 150 mm in internal diameter and 410 mm in height. The instrumentation includes: top and base load cells; 1000 kPa capacity pore water pressure transducers at mid-height, the base and halfway between the mid-height and base (i.e. at quarter-height); a 10 kN electromagnetic load frame; and a data logger and controller. The stress applied via a cap to the top of the specimen is measured by the top load cell connected to the loading piston, and the stress transmitted to the base is measured by the base load cell. The difference between the measured applied load at top and transmitted load to the base gives an indication of the combined piston and wall friction losses. The 410 mm height of the cell accommodates slurry samples to settle between layers, to make a test specimen with a hight of 300 mm high.

The stress distribution along specimens is difficult to measure, thus this distribution is commonly assumed in a linear or parabolic form [18,19], as shown in Fig. 2. It is intuitive that, the stress distribution is concave downward because of friction losses.

Generally, the average stress and pore water pressure of specimens can be calculated using,

$$\sigma_{ave} = \sigma_t - \beta_1(\sigma_t - \sigma_b) \tag{1}$$

and,

$$u_{ave} = \beta_2 u_b \tag{2}$$

where β_1 and β_2 are average coefficients. For linear and parabolic assumptions, $\beta_1 = \beta_2 = 0.5$ and $\beta_1 = \beta_2 = 0.67$, respectively.

As shown in Fig. 3, a slice of the specimen of infinitesimal thickness dz bounded by the walls of a large consolidometer may be considered. The vertical stress $\sigma(z)$ and $\sigma(z + dz)$ are applied respectively to the top and bottom of the slice, and the difference between them is the friction loss $f(z)$, which is proportional to the normal effective stress σ'_n developed on the wall. If the coefficient of proportionality is α, then the wall friction is given by,

$$\frac{d\sigma}{dz} = \alpha\sigma'_n \tag{3}$$

where $\alpha = tan\phi$ given by Coulomb's friction law, and ϕ is the wall friction angle.

The friction angle can be determined from direct shear box testing, with the material of the consolidometer wall filling the bottom half of the box and the soil filling the top half. For the purposes of this paper, the wall friction values recommended by NAVFAC were adopted [28]. Potyondy reported the results of a large number of direct shear box tests for various structural materials, and soil types at different pre-set water contents [29], which indicated much lower wall friction values than those recommended by NAVFAC.

The wall friction developed in a saturated soil may be given by Coulomb's friction law:

$$f = \sigma'_n \tan\phi \tag{4}$$

where ϕ is friction angle on the interface.

Including the radius of the large consolidometer r, the at rest lateral earth pressure coefficient against the wall K_0, and the wall friction angle ϕ, the coefficient of proportionality α is given by:

$$\alpha = \frac{2r\pi}{r^2\pi} K_0 \tan\phi \tag{5}$$

where K_0 is the lateral earth pressure coefficients at rest which can be estimated theoretically by Poisson's ratio.

4. Theory of large-strain consolidation

4.1. Large-strain formulations

Once a slurry settles to form particle-particle contact, the effective stresses develop under self-weight and any applied vertical stress. The strain accompanying the consolidation of settled slurries is too large to satisfy the assumptions of small strain, constant hydraulic conductivity, and constant compressibility. Gibson's general equation for large-strain consolidation is widely accepted [5], and can be expressed in volume fraction form as: