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A framework for coupled consolidation-desiccation behaviour of clay slurries

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ABSTRACT

A framework is proposed to understand coupled consolidation-desiccation in clay slurries using effective stress and soil suction as state variables. Constitutive surfaces were derived from best-fit equations for reference curves where one state variable was kept at 1 kPa and the other was varied up to 10^6 kPa. Results indicated that volume compressibility comprises of apparent pre-consolidation up to 100 kPa beyond which a single best-fit curve is valid. Similarly, the theoretical virgin compression line (specific gravity dependant), indicated that both state variables have the same effect up to the air entry value (1000 kPa at a void ratio of 1.8) beyond which void ratio reduces more readily under effective stress than under soil suction. Likewise, hydraulic conductivity remained saturated up to the air entry value and varied from 10^{-9} m/s to 10^{-12} m/s. Finally, the unsaturated hydraulic conductivity correlated well with empirical relationship up to 10^{-14} m/s beyond which vapor flow became dominant.

1. Introduction

Mining operations generate slurry wastes that pose significant environmental hazards because of their loose state. In particular, slurries containing active clays require long time to undergo consolidation. Typical examples include oil sand tailings in Alberta, Canada [1] and phosphate tailings in Florida, United Stated of America [2]. To augment consolidation, slurries are disposed off in above ground containment facilities where desiccation can also occur under the prevalent climatic regime [3]. The simultaneous dewatering is a viable tailings management option for several mine sites around the globe, particularly those in arid and semi-arid regions such as South America, Australia and Africa [4]. Therefore, there is a need to understand the coupled processes of consolidation and desiccation to plan slurry depositional schemes, determine storage capacities, and estimate closure times.

Consolidation and desiccation occur under independent stress state variables, namely; effective stress (σ') which is the stress transferred through the soil particles under saturated conditions [5] and soil suction (ψ) which is the stress transferred through the soil pores under unsaturated conditions [6]. The two stress state variables are mathematically expressed as $\sigma' = \sigma - u_w$ and $\psi = u_a - u_w$, where σ is total stress, u_a is pore air pressure, and u_w is pore water pressure. When deposited under a given initial water content (based on industrial specifications), slurries undergo self-weight settling and gradually develop effective stresses to become soil-like by overcoming inherent electrochemical interactions [7]. Furthermore, effective stress governs slurry consolidation (load dependent deformation due to excess pore pressure dissipation) and is useful in understanding creep (time dependent deformation at constant σ'). The electrochemical interactions are difficult to quantify and the resulting osmotic suction is inconsequential for a given pore fluid composition [8,9] and, as such, is included in soil suction. The selection of the above mentioned stress state variables for clay slurries is a modification from soils, which use net normal stress and soil suction as stress state variables.

The two dewatering regimes can be combined using three-dimensional plots to develop constitutive surfaces for volume compressibility (e versus σ' and ψ plot) and hydraulic conductivity (k versus σ' and ψ plot): where e is void ratio and k is hydraulic conductivity. Such surfaces represent the interrelationship of stress state variables and allow the determination of soil properties under various conditions of loading and desaturation. The determination of constitutive surfaces requires advanced triaxial or odometer testing [10,11]. Relationships at constant stress values have been developed for soils [12–14] as well as for slurries [10,15,16]. However, testing limitations (customized laboratory equipment, long time commitment, data interpretation expertise) and three dimensional shrinkage have resulted in partial understanding of soil behavior. The alternative approach is to empirically

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construct the constitutive surfaces using measured data for reference curves and to determine the intermediate behaviour at constant ψ or constant σ' planes by linear interpolation [17,18]. The selection of the above mentioned relationships is distinct from soils, which use volume compressibility and a constant k.

This paper aims to develop a framework for coupled consolidation-desiccation behavior of clay slurries. Initially, reference curves (at 1 kPa nominal stress) for volume compressibility and hydraulic conductivity were developed using laboratory test data. Next, best-fit equations were obtained to describe the family of curves for both stress state variables. Finally, three-dimensional constitutive surfaces were empirically constructed for volume compressibility and hydraulic conductivity by linear interpolation using the new equations.

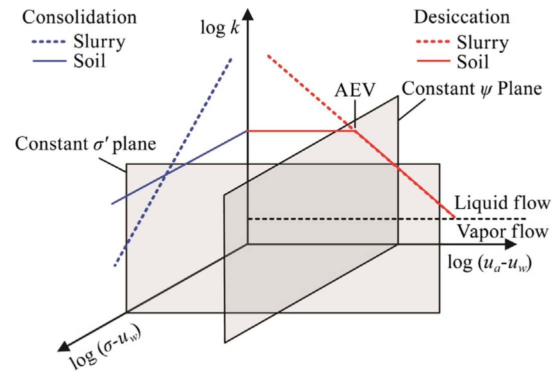

Fig. 2. Conceptual constitutive surface for hydraulic conductivity.

2. Literature review

Fig. 1 gives a conceptual constitutive surface for volume compressibility during consolidation (saturated) and desiccation (unsaturated) using semi-logarithmic plots. The void ratio of soil decreases with increasing σ' such that there is an initial low decrease (almost horizontal line) due to pre-consolidation stress followed by a relatively high decrease (straight line with downward slope) which represents virgin compression. In contrast, volume compressibility of slurries under the same stress state variable is given by a smooth curve that cannot be divided into distinct straight-line components. This behavior has been well investigated for soils [5,19,20] and slurries [2,21,22]. For clay slurries, the relationship is governed by the presence of apparent preconsolidation (due to initial conditions, electrochemical interactions, tortuous drainage, and thixotropic strength) at high void ratios [23].

Similar corresponding behaviors for soils and slurries can be envisaged under unsaturated conditions. This part of the constitutive surface is a form of the soil water characteristic curve (SWCC). The void ratio reduction due to ψ increase is similar to volume compressibility up to the air entry value (AEV) beyond which the slope is relatively flat. This is because the void ratio achieved through desiccation is usually higher than that achieved through consolidation [24]. The curve becomes asymptotic to the abscissa at the residual conditions at which point the soil achieves minimum void ratio (e_{min}). The SWCC must be studied along with a shrinkage curve (void ratio versus water content) for soils that undergo volume decrease due to the application of soil suction. This behavior has recently been investigated for expansive soils [25,26] and tailings slurries [27,28]. For clay slurries, the air entry value and the residual soil suction have been found to correlate with the plastic limit and the shrinkage limit, respectively [29].

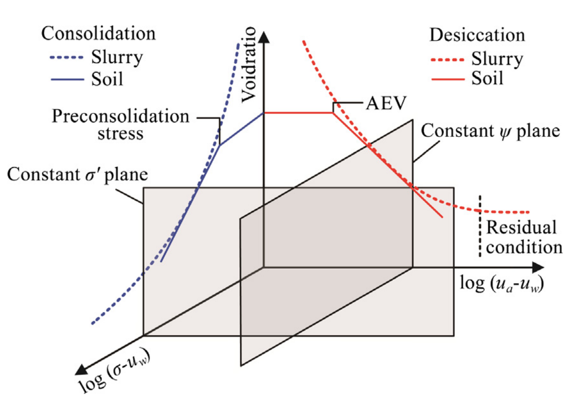

Fig. 1. Conceptual constitutive surface for volume compressibility.

Fig. 2 gives a conceptual constitutive surface for hydraulic conductivity during consolidation (saturated) and desiccation (unsaturated) using logarithmic scales. The hydraulic conductivity of soils is considered to be constant with σ' increase due to small decrease in void ratio [5,30,31]. For slurries, an increase in σ' causes the hydraulic conductivity to decrease because of a significant decrease in void ratio [7,32–34]. For clay slurries, hydraulic conductivity is governed by small pore throats and tortuous flow paths [1,29,35].

Under increasing ψ, the saturated hydraulic conductivity (k_{sat}) for soils is constant up to AEV (due to small reduction in e) beyond which the unsaturated values decrease by several orders of magnitude [36–38]. The lower limit for liquid flow is difficult to determine but can be taken as 10^{-14} m/s (corresponding to residual conditions) beyond which vapor flow governs [39]. For clay slurries, Khan and Azam [29] reported that the hydraulic conductivity is not constant for ψ less than AEV because of decrease in void ratio.

3. Research methodology

A clay possessing high water adsorption characteristics was used. The liquid limit (LL), plastic limit (PL), and shrinkage limit (SL) were 180%, 60%, and 20%, respectively [23]. The consolidation behavior of the clay, at an initial water content (w) equal to the liquid limit and determined using a conventional odometer test alongside a bench-top centrifuge test, was reported by Khan and Azam [23]. Additional centrifuge tests were conducted at $w > LL$ (up to 2.5 LL) and the results are presented in this study. Likewise, the desiccation behavior of the clay, at variable initial w (1.0–2.5 LL) and determined through soil suction tests along with evaporation tests, was reported by Khan and Azam [29].

Test results from the above investigations are presented in the form of the two constitutive relationships. Likewise, the hydraulic conductivity under both saturated and unsaturated conditions is presented as a function of void ratio. Best-fit equations were obtained to describe the family of curves for both stress state variables. Three-dimensional constitutive surfaces were empirically constructed for volume compressibility and hydraulic conductivity by linear interpolation using the best-fit equations, as described by Zhang [18].

4. Results and discussion

Fig. 3 gives the volume compressibility of the investigated clay slurry. With an increase in σ', the void ratio of the 2.5 LL sample sharply decreased from 12.8 at 1 kPa to 8.25 at 10 kPa and gradually decreased to 4.0 at 100 kPa and then to 1.5 at 1440 kPa. A weibull function was found to best fit this behaviour, similar to oil