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A semi-empirical swell prediction model formulated from 'clay mineralogy and unsaturated soil' properties☆

Anand J. Puppala [a,*], Aravind Pedarla [a], Laureano R. Hoyos [a], Claudia Zapata [b], Tejo V. Bheemasetti [a]

[a] Box 19308, Department of Civil Engineering, The University of Texas at Arlington, Arlington, TX 76019, United States
[b] Box 875306, School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ 85287, United States

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ABSTRACT

Swell behavior of expansive clays is an inherent property that can be better explained through its hydro mechanical volume change behavior arising from soil attributes like matric suction and clay mineralogy information. Previous swell related modeling studies have not incorporated these attributes for swell behavior, thereby leading to poor to erroneous characterization practices. Both chemical and hydrological attributes of the soils are targeted in this expansive soil modeling. Eight natural expansive soils were collected and their swell strains were measured under different confining pressure conditions. Soil suction properties of expansive soils as well as soil water characteristic curves (SWCC's) were determined using standard measurement procedures including pressure plate and filter paper techniques. Slope of the paths traversed by the soil specimens in a void ratio — soil matric suction framework are determined and used as mechanical input parameters for the heave modeling. A new parameter, Mechanical Hydro Chemical Parameter (MHCP) is used that accounts for both matric suction and clay mineralogy information. This parameter is correlated with swell property measurements and the correlations developed provided reliable and reasonable swell property predictions. Independent validations with other soils are still needed for further enhancement of the MHCP framework for more reliable predictions.

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1. Introduction

Expansive soils undergo moderate to large volume changes during the seasonal moisture content fluctuations and these changes can inflict moderate to severe damages to pavements and other overlying infrastructure including one to two story buildings. Annual losses due to expansive soil damages costs sum up to several millions of dollars and earlier studies reported that these damage costs are more than those caused by natural disasters including tornadoes and earthquakes (Jones and Holtz, 1973; Chen, 1988; Puppala et al., 2011). Researchers have either used or relied on simple index soil properties to characterize and understand expansive soils (Chen, 1988; Abduljauwad, 1993; Al-Rawas, 1999; Puppala et al., 2004, 2013). These simple characterizations appear to provide problematic characterization leading to erroneous foundation support to the structures built above them.

For example, soils with same index properties will have different volume related behavioral changes due to different clay mineralogies. In addition, external environmental conditions at each site will lead to different volume change patterns (Teresa et al., 2004; Puppala et al., 2004; Puppala and Cerato, 2009; Chittoori and Puppala, 2011). Characterizations that do not consider both compositional and environmental conditions appear to provide poor characterizations and this practice should explain the reasons for no decrease in annual maintenance costs from expansive soil induced damages. This has provided impetus for the present research which is aimed at an in-depth understanding of the swelling mechanisms of soils based on their inherent soil mineralogy properties and unsaturated soil conditions. These studies lead to more rational approaches for expansive soil characterization.

Soil matric suction plays an important role in the swelling behavior of soils as majority of these soils are in unsaturated state in the real field conditions. Many researchers including Fredlund and Morgenstern (1996); Alonso and Gens (1999), Saiyouri et al. (2004); Yusuf and Erol (2007), Puppala et al. (2011) and others have attempted to map the variation of soil matric suction parameters with respect to swelling related behavioral patterns. Fredlund and Morgenstern (1996); Snethen (1979) and Alonso and Gens (1999) have studied and predicted the vertical swell movements of natural and artificial soil mixtures using semi-empirical and mathematical models based on unsaturated soil related framework models. Delage et al. (1998); Hussein (2001) and Saiyouri et al. (2004) have studied the hydro mechanical and visco-plastic behaviors of compacted unsaturated clays based on wetting and drying processes. Zhan et al. (2007) studied swell behaviors of both natural and

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* Corresponding author.
E-mail address: anand@uta.edu (A.J. Puppala).

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remolded soil specimens in order to determine their complex soil water interactions in unsaturated expansive clays.

The dominant role played by clay mineralogy is identified and included in the current swell prediction model, as soils with different chemical mineralogies will have different swell behaviors. Saiyouri et al. (2004) concluded that the differences in clay swelling are attributed to the nature of the saturating cations (Na or Ca) present in the fluid medium and this was later validated by Yusuf and Erol (2007) by studying Na-bentonite mixtures which explained the dependency of soil suction on compaction water content, dry density and clay mineral content.

In expansive soils, the most commonly occurring clay minerals documented in the literature are Kaolinite, Illite and Montmorillonite (Mitchell and Soga, 2005). Montmorillonite is a highly reactive expansive mineral in nature and as a result, the presence of this mineral causes major volume changes in the soils and is hence proven to be challenging to stabilize these mineral rich soils (Mitchell and Soga, 2005; Pedarla, 2013). Realizing the importance of clay mineralogy quantification in characterizing expansive soils, Chittoori and Puppala (2011) formulated a methodology for the quantification of these three dominant clay minerals in a given soil using three measured chemical soil properties namely, Cationic Exchange Capacities (CEC), Specific Surface Area (SSA) and Total Potassium (TP). This procedure was validated using artificial clay mixtures of known mineralogies and the same method has been followed in the current research for the determination of clay minerals of the present soils.

From these previous studies, it was evident that the clay mineralogy of the soils in unison with unsaturated properties was not taken into consideration for the swell prediction models. Hence, in this research, an attempt has been made to understand the relationship of soil matric suction along with clay mineral content on the swell behavior of the soils. Investigations were conducted on natural expansive soils followed by an analysis that accounts for mechanical (loading and volume change related), hydro (moisture related), and chemical (mineralogy related) analysis in unison to develop a more reliable characterization framework. The following sections describe the experimental program details along with the modeling analysis as a part of this framework development.

2. Experimental program

A total of eight soils of known expansive nature are considered and sampled for the present research. All eight soils were first subjected to basic soil classification and plasticity tests. Standard Proctor tests were also conducted on the soils to establish their compaction relationships and a summary of these test results including maximum dry unit weight (MDUW) and optimum moisture content (OMC) details are presented in Table 1.

From the test results, it was observed that Grayson soil exhibited the highest plasticity index property (PI) and percent clay content when compared to other seven soils. A static compactor, as suggested in the AASHTO T-307 method for preparing fine-grained soil specimens, was used in the present research. With this static compaction method, soil specimens with targeted moisture content and dry unit weight (density) levels can be prepared in a short time without layering issues which is commonly found in impact compaction techniques. Standard size specimens of 6.35 cm (2.5 in.) in diameter and 2.54 cm (1 in.) in height were prepared and used for the one dimensional vertical swell and swell pressure testing. Sample sizes of 5.08 cm (2 in.) in diameter and 10.16 cm (4 in.) in height were prepared for the 3-D Swell strain testing. A height to diameter ratio of 2 was selected for 3-D swell strain testing. All the soil specimens were compacted to 95% MDUW for swell strain testing as this condition represents soil compaction state in the field which is close to the dry side of 95% MDUW.

2.1. One dimensional swell strain test

In the experimental program, standard ASTM D-4546 procedure was followed for the determination of one dimensional vertical free swell strain of a compacted or intact clay sample. An initial seating load of 7 kPa (1 psi) was first applied to the specimen ensuring proper contact of specimen with load assembly. Once proper contact was achieved, the setup was inundated with deaired water from both specimen ends and then the specimen was allowed to undergo swelling. Measured clay mineralogy and one dimensional vertical swell strain test results of all eight soils are presented in Table 2.

2.2. Three dimensional volumetric swell strain test

Standard one dimensional consolidometer studies for heave prediction in swelling clays have been studied by many researchers and have proven to be reasonably effective in assessing the swell behavior of clays (Holtz and Gibbs, 1956; Lambe and Whitman, 1969). These tests represent specimens tested under rigid lateral boundary conditions. In reality, the soils are confined in all three dimensions and they will undergo swell strains in all three directions which contribute to overall volumetric swell strains. Hence, in the current research, a 3-D swell strain apparatus was designed and used. Fig. 1 presents both the test chamber and the 3-D swell test apparatus used in the present experimental program. Details of the test apparatus and operating principles are described in detail by Pedarla (2013) and Pedarla et al. (2015). Radial strains experienced by the soil specimen in the lateral direction are recorded from the volumes of the water drained from the burette measurements.

The soil specimen encased in the chamber was inundated with the water in an open large tank and then the samples were allowed to undergo swelling in both diametrical and vertical directions. A latex membrane was used to confine the soil specimen from surrounding water. De-aired water was used to provide isotropic confinement on the soil specimen during the test, similar to a triaxial test. Calibration tests were first conducted with a solid metal cylinder to measure the volumetric strains experienced by the test chamber at different confining pressure conditions. These readings are used to establish the corrections that need to be applied to the volumetric deformations recorded of the test specimens. Fig. 2(a) and (b) presents the illustrations of the test in progress. The vertical, radial and volumetric strain readings were

Table 1
Basic soil classification and soil index properties.

Soil	Liquid limit	Plasticity index (PI)	Specific gravity Gs	USCS classification	Clay content (%)	MDUW (kN/m^3)	OMC
Anthem	48	27	2.72	CL	32	16.86	18
Burleson	55	37	2.72	CH	52	16.01	19
Colorado	63	42	2.70	CH	46	16.17	19
Grayson	75	49	2.73	CH	55	14.28	24
Keller	25	11	2.70	CL	34	18.53	14
Oklahoma	41	21	2.80	CL	30	15.62	24
San Antonio	67	43	2.79	CH	52	15.76	22
San Diego	42	28	2.72	CL	23	17.02	17

Table 2
Clay mineralogy and one dimensional vertical swell strain test results.

Ranking		Clay mineral content			1-D swell strain (%)
Soil	PI	% Montmorillonite	% Illite	% Kaolinite	95% MDUW
Grayson	50	43.3	24.0	32.7	9.8
Colorado	42	35.7	35.0	29.3	8.2
San Antonio	43	37.8	30.9	31.3	7.3
Burleson	37	33.7	19.6	46.7	5.5
Keller	11	21.9	18.4	59.7	5.6
Anthem	27	25.2	24.4	50.4	4.5
Oklahoma	21	19.7	70.0	10.3	3.8
San Diego	28	26.9	25.3	47.8	3.4