**A SEMI-EMPIRICAL SWELL PREDICTION MODEL FORMULATED FROM ‘CLAY
MINERALOGY AND UNSATURATED SOIL’ PROPERTIES**

**Anand J. Puppala, Ph.D., P.E.
Distinguished Professor
Box 19308, Department of Civil Engineering
The University of Texas at Arlington
Arlington, Texas 76019
E-mail: anand@uta.edu**

**Aravind Pedarla, Ph.D.
Post-Doctoral Fellow
Box 19308, Department of Civil Engineering
The University of Texas at Arlington
Arlington, Texas 76019**

**Laureano R. Hoyos, Ph.D., P.E.
Professor
Box 19308, Department of Civil Engineering
The University of Texas at Arlington
Arlington, Texas 76019**

**Claudia Zapata, Ph.D., P.E.
Associate Professor
Box 875306, School of Sustainable Engineering and the Built Environment
Arizona State University
Tempe, Arizona 85287**

**Tejo V. Bheemasetti, Ph.D.
Post-Doctoral Fellow
Department of Civil Engineering, Box 19308
The University of Texas at Arlington
Arlington, Texas 76019**

**A Paper Submitted for Possible Publication in
ENGINEERING GEOLOGY**

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 sampled 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, mechanico-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 outside soils are still needed for further enhancement of the MHCP framework for more reliable predictions.

Keywords: expansive soils, swell behavior, clay mineralogy, soil suction, swell prediction model

1 INTRODUCTION

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

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

22 Soil matric suction plays an important role in the swelling behavior of soils as majority of
23 these soils are in unsaturated state in the real field conditions. Many researchers including

Fredlund and Morgenstern (1976), Alonso et al. (1999, 2005), Saiyouri et al. (2004), Yusuf and Erol (2007), Agus et al. (2010), Puppala et al. (2011), Pedarla et al. (2015) and others have attempted to map the variation of soil matric suction parameters with respect to swelling related behavioral patterns. Fredlund and Morgenstern (1976), Snethen (1979) and Alonso et al. (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 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 cause major volume changes in the soils and is hence proven to be challenging to stabilize these mineral rich soils (Mitchell and Soga, 2005; Pedarla et al. 2015). Realizing the importance of clay mineralogy quantification in characterizing expansive soils, Chittoori and Puppala (2011)

1 formulated a methodology for the quantification of these three dominant clay minerals in a given
2 soil using three measured chemical soil properties namely, Cationic Exchange Capacities (CEC),
3 Specific Surface Area (SSA) and Total Potassium (TP). This procedure was validated using
4 artificial clay mixtures of known mineralogies and the same method has been followed in the
5 current research for the determination of clay minerals of the present soils.

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

16 **EXPERIMENTAL PROGRAM**

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

22 From the test results, it was observed that Grayson soil exhibited the highest plasticity
23 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.

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.

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, 1959). 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

1 contribute to overall volumetric swell strains. Hence, in the current research, a 3-D swell strain
2 apparatus was designed and used. Figure 1 presents both the test chamber and the 3-D swell test
3 apparatus used in the present experimental program. Details of the test apparatus and operating
4 principles are described in detail by Pedarla (2013) and Pedarla et al. (2015). Radial strains
5 experienced by the soil specimen in the lateral direction are recorded from the volumes of the
6 water drained from the burette measurements.

7 The soil specimen encased in the chamber was inundated with the water in an open large
8 tank and then the samples was allowed to undergo swelling in both diametrical and vertical
9 directions. A latex membrane was used to confine the soil specimen from surrounding water. De-
10 aired water was used to provide isotropic confinement on the soil specimen during the test,
11 similar to a triaxial test. Calibration tests were first conducted with a solid metal cylinder to
12 measure the volumetric strains experienced by the test chamber at different confining pressure
13 conditions. These readings are used to establish the corrections that need to be applied to the
14 volumetric deformations recorded of the test specimens. Figure 2 (a) and (b) present the
15 illustrations of the test in progress. The vertical, radial and volumetric strain readings were
16 measured against elapsed time period for all the soils and the details of volumetric swell strains
17 of Colorado soil specimens is presented in Figure 3.

18 Table 3 summarizes the vertical, radial and volumetric strains measured for all eight soils
19 at 95% MDUW and OMC conditions. Overall, it was observed that the soil specimens
20 experienced low radial strains when compared to vertical strains during the isotropic
21 confinement. This is attributed to the fact that the soil expansion is small as the specimen was
22 confined all around with moderate confining pressure; additionally, this confining pressure
23 resists the soil repulsive forces induced from soil expansion from the diffused double layer

1 systems of the clay particles. Hence, the volumetric swell strain measurements are smaller in the
2 present 3-D swell tests when compared to the same under 1-D swell tests.

3 Among all eight soils, it was observed that Grayson soil specimen exhibited the
4 maximum amount of swell strains in vertical, radial and volumetric directions and San Diego soil
5 specimen exhibited the least amount of swell strains. The following sections describe the
6 determination of unsaturated soil properties from SWCC studies and related modeling analyses
7 to study the expansive behavior of these soils.

8 **DETERMINATION OF UNSATURATED SOIL PARAMETERS**

9 The soil water characteristic curve (SWCC) represents the fundamental behavior of a soil
10 that correlates soil matric suction with moisture content of the soil. In this research, two methods,
11 the filter paper method and the pressure cell using axis translation technique were used to
12 determine the SWCCs over a wide range of soil suction conditions. For example, the filter paper
13 method (using ASTM D5928-94 - Standard Test Method for Measurement of Soil Suction) was
14 utilized to determine the matrix suction of the soil specimens when the soil suction are around
15 500 kPa to 100,000 kPa. Pressure cell apparatus was utilized for suction measurements for soils
16 at low to medium unsaturated state with soil suctions less than 500 kPa. Figures 4 and 5 present
17 the SWCCs measured for low plasticity (CL) and high plasticity (CH) clayey soil specimens
18 compacted at 95% MDUW condition. For each test curve, air entry suction values, saturated and
19 residual moisture contents are determined and provided. Also, the SWCC experimental data is
20 modeled and fitted with Van Genuchten (1980) and Fredlund and Xing (1994) models. Summary
21 of SWCC test results and corresponding model attributes are presented in Table 4.

ASSESSMENT OF SWELL BEHAVIOR

The mechanical volume change behavior of soil specimens under a given overburden loading condition can be effectively evaluated by accounting for their inherent mineralogy and unsaturated soil properties. The present model is hence termed as ‘Mechanical-Hydro-Chemical’ or MHC modeling framework, which aims at understanding of the soil’s tendency to absorb moisture content while undergoing volume changes. Variations of compaction void ratio with change in soil matric suction is considered and included here as the volume change of soils occur from mechanical contributions. Changes in soil matric suction state of the soils represent the moisture state condition of the soil specimen, which can influence the moisture flow pattern within the soils resulting their volume changes. This is also considered as hydro related conditions contributing to the overall soil volume changes as moisture access to soil particles contribute to swell related volume change.

Clay mineralogy of the soil constituents is the chemical parameter contributing to overall swell behavior of expansive clay as the chemical nature of expansive clay minerals will result in the adsorption of the moisture as a part of their diffused double layers. This in turn will contribute to overall soil swelling. The proposed MHC model framework hence captures all the aforementioned soil properties that result in soil heaving. These properties include initial matric suction, air-entry suction, slope of soil suction-void ratio, mineral content and the percentage mineral Montmorillonite. All these are measured from the present SWCC, mineralogy and swell related soil tests conducted on all eight soils.

Prior to the development of the ‘Mechanical Hydro Chemical’ or MHC model, a few of the following assumptions are used and these are:

1. Montmorillonite clay mineral contributes to a major portion of the total soil heaving or swelling behavior of a soil when compared to Illite and Kaolinite clay minerals. A new swell factor ‘SF’ pertaining to individual clay minerals is introduced. Several other clay minerals are not accounted for as they are not considered to be dominant in the given soils.
2. The variation of compaction moisture content to soil matric suction in the ‘void ratio (e) – Moisture Content (w) – log ‘Soil Suction’ (log ψ)’ graph derived from both SWCC and swell tests is assumed to be linear.
3. SWCC of the expansive clays is assumed to be a major factor in governing the overall soil swell behavior. Other parameters such as grain size and pore size distributions are not explicitly considered in this modeling. They are however implicitly accounted for in the analysis by using clay fraction in soils as another parameter.
4. Soil drying or desorption and wetting curves of the SWCCs are considered to provide the same curve, i.e. the hysteresis effects on the SWCCs are neglected.
5. The current model considers that the matric suction of the soils only influences heaving of expansive clays.

Chemical Mineralogy Factors of Clay Fraction

Swelling behavior of compacted clay is often affected by the type and amount of mineral present in the clay fraction. In the current model a swell factor (SF) is attached to each of the three dominant mineral types present in the clay fraction of the soil. Montmorillonite mineral being the dominant swelling clay mineral and has the highest diffused double layer capacity (Mitchell and Soga, 2005) was assigned a swell factor of 90. Similarly, the swell factors (SF)

considered for Illite and Kaolinite minerals are 9 and 1, respectively. These values are generated based on the ratio of their respective individual diffusive double layer thickness generated for a crystal thickness of 1 Å (i.e. Montmorillonite - 42, Illite - 3, Kaolinite -1 for a 1Å crystal). The total contribution of swell factors from these three minerals in a soil specimen was set to a maximum of 100.

In this model, a chemical factor, CF parameter which represents the chemical activity of a particular clay fraction in a soil specimen is introduced and is given by the following Eq.1.

$$C = CF \times \sum_{i=1}^n SF * f_i \quad (1)$$

where C is the chemical factor for particular clay, CF is the clay fraction, SF is the swell factor, 'f_i' is the fraction of particular mineral in the clay fraction.

Mechanical-Hydraulic Factor for Soils

The mechanical volume change attributes of clay are represented best by studying the variation of matric suction with void ratio during the swelling process. Hence, the cumulative variation of void ratio, matric suction and moisture content is considered as the physio-mechanical attribute to provide the swelling behavior of soil. Figure 6 presents a schematic of the variation of mechanical soil parameters with corresponding swell induced volume changes.

Where, e_i, w_{initial} and ψ_{initial} are the void ratio, moisture content and soil matric suction at initial compaction condition. Similarly, e_f, w_{final} and ψ_{final} are the void ratio, moisture content and soil matric suction at saturation condition, i.e. at the end of swell property testing.

The variation of void ratio with moisture content and corresponding soil matric suction change is studied and plotted. This plot is termed as 'void ratio (e) – Moisture Content (w) – log Soil Suction (logψ)' plot (e-w-logψ plot). The e-w-logψ plot is unique for a given soil type as swell governing factors like soil matric suction and void ratio states are considered and included.

The variation of soil matric suction with moisture content is assumed to be linear in the current modeling analysis. Hence, the curve results in a linear pattern for the variation of compaction void ratio with soil matric suction condition.

Figure 7 presents the schematic for the determination of α from void ratio and matric suction plot along with the idealized and actual paths exhibited by soil specimen. Where, e_i is the initial void ratio, e_f is the void ratio at saturation, $\psi_{initial}$ is the initial matric suction in the soil specimen before swelling, $\psi_{air-entry}$ is the air entry value suction, ψ_{final} is the final matric suction close to saturation and α is the slope of idealized suction void ratio path. Initially the soil specimen has high matric suction ($\psi_{initial}$) and a relatively low void ratio (e_i). The moisture content and matric suction relationship via SWCC is correlated to assess corresponding void ratio, there by resulting in e-w-log ψ plot. Prior to swelling, the soil state is at an initial point on the curve 'A' and with moisture imbibation it reaches the saturation stage at point 'C' on the plot. The actual path traversed by the soil specimen is A-B-C, where as for characterization purposes importance is given to the slope of the imaginary path A-C as shown in Figure 7. The slope of soil matric suction (X-axis) and void ratio (Y-axis) plot (α) is determined by joining the initial and final points of the imaginary path traversed by the soil during the swelling process.

During the swelling process the matric suction in the soil specimen decreases with an increase in moisture content along with an increase in the initial void ratio. Though this trend is non-linear, for the simple formulation sake, a liner variation between these properties is considered here. Hence, the slope of the idealized matric suction-void ratio path is given by the following Eq. 2.

$$\alpha = \frac{(e_f - e_i)}{(\log(\psi_{final}) - \log(\psi_{initial}))} \quad (2)$$

The value of ψ_{initial} was high when compared to ψ_{final} which leads to a negative slope α . The current 'Mechanical and Hydro' effect is formulated based on the magnitude of α and the negative effect of slope is neglected. As the soil specimen attains higher degree of soil saturation and swell, the void ratio of the soil specimen increases. This behavior is noticed in all e-w-log ψ plots of the eight expansive soils which are presented in the following section.

e-w-log ψ plot for Anthem Soil

Anthem soil which was compacted at 95% MDUW and OMC condition was then tested to study SWCC and swell behaviors. The swell behavior exhibited by Anthem soil specimen on an e-w-log ψ plot is determined from both these tests and the results are presented in Figure 8. Figure 9 presents the e - log ψ plots for all the test soil specimens compacted at 95% MDUW where moisture

During the swelling process, Anthem soil specimen experienced a void ratio change from 0.716 to 0.786. Correspondingly, the gravimetric moisture content has increased from an initial 18.0% to a final value of 26.5%. With the help of SWCC results, soil matric suction values are correlated from the corresponding moisture contents indicating an initial matric suction of 450 kPa which decreased to 10 kPa at close to saturation. Table 5 presents the slopes of matric suction-void ratio plots of all the eight soils studied for soil matric suction behavior. The slope angle, α determined as a slope of void ratio - matric suction plot was the highest for Grayson clay and the least for San Diego clay.

Combined Mechanical, Hydro, and Chemical Parameter (MHCP)

A new parameter termed here as the Mechanical Hydro Chemical Parameter (MHCP) has been formulated by including the cumulative effects from soil swell governing parameters such as void ratio, initial soil matric suction, air entry suction, percentage clay fraction and percentage

Montmorillonite mineral fraction, respectively. From previous literature, it is clear that soil swelling is directly influenced by mineralogy and activity of clay minerals. For the current model, the combined effects of physical, mechanical and chemical parameters was considered for interpreting swell behaviors. The interdependent coupled effects from clay mineralogy and soil suction are designated by a multiplication factor “ π ”. Hence, the total Mechanical Hydro Chemical Parameter (MHCP) can be determined using the following Eq. 3.

$$MHCP = \pi(\alpha, C) \quad (3)$$

Where MHCP is the Combined Mechanical Hydro Chemical Parameter, α is the mechanical-hydro parameter and C is the chemical parameter. The negative effect on the slope is currently neglected in the determination of MHCP because of the known fact that the decrease in matric suction is imminent during saturation and swelling process in a soil specimen. The MHCP for all the eight expansive soils are determined from the e-w-log ψ plots and the corresponding chemical parameters from chemical mineralogy. Table 5 presents the determination of MHCP from chemical parameter and mechanical hydro parameter determined for each soil.

For the test soils, the MHCP ranged from 0.070 to 3.431. Grayson soil due to its high Montmorillonite mineral content and α value has attained the highest MHCP value of 3.431 whereas San Diego soil exhibited the smallest MHCP value of 0.070, which is attributed to low α and C parameters.

MHC model is then formulated on the basis of the unique MHCP values determined for each soil which are then correlated with the measured swell strains and pressures of the test soils. Figures 10 and 11 present the variation of MHCP with measured swell strains under different boundary conditions.

Overall, MHCP value representing both chemical and soil suction parameters demonstrated a direct influence on the swelling strains exhibited by the soil. Test data was fitted with a non-linear model and this modeling information is included in the same figure. MHCP models for prediction of swell strains and swell pressures provided reliable modeling of the present experimental data. Coefficient of determination values of the fitted curves are around 0.80 which could be attributed to the assumed swell factor, hysteresis effects and others. From the present test results, it can be concluded that the swell properties are directly proportional to the MHCP values. The formulation of this swell strain in uni or three dimensional state is presented in the following Equation:

$$\epsilon_{swell(1-D,3-D)} = a (MHCP)^b \quad (4)$$

Where ‘a’ and ‘b’ are modeling parameters and are dependent on the test related boundary conditions like type of swell test, confinement and other environmental factors including compaction moisture content and dry unit weight conditions. From the models generated based on the present eight test soils, the ‘a’ parameter ranged from 4.49 to 7.53 and ‘b’ parameter ranged from 0.25 to 0.34. Future studies using a wide range of expansive soils will further refine the modeling parameters and the MHCP framework model. Influential factors such as pore distribution and water salinity also play a major role in swell behavior. Overall, it can be stated that this model proven to be reliable and hence recommended for future practice. It is understandable that the potential use of this model requires more parameters and hence more advanced soil testing that can be expensive. Considering the potential high costs from the damage to civil infrastructure by expansive soils, initial additional tests are recommended which would improve the characterization practice.

SUMMARY AND CONCLUSIONS

Swelling behavior of eight natural expansive soils are studied and analyzed using conventional and novel testing methods, encompassing both vertical and volumetric swell strain and swell pressure behaviors. The slope of the path traversed by the soil specimen on a matric suction and void ratio plot (α) is a unique representation of the hydro mechanical change undergoing by the specimen during swelling. The measured C and α parameters exhibited a direct relationship to measured swelling strains of the eight natural expansive clays. A new MHC Parameter is formulated based on the coupled effects of mechanical-hydro related and chemical mineralogical properties of expansive soils. C and α parameters were compared to the measured swell strains of the soil specimens compacted at two different compaction dry density conditions and corresponding swell prediction equations were derived.

The current swell prediction models were generated based on a limited number of natural expansive clays and pertains to a specific suction (0-1200 kPa) and void ratio range (0.5-1.25). More validation studies are currently being pursued to strengthen the model and to better refine the swell factors of the individual mineral crystals which are currently assumed. Current studies are being focused on including pore size distribution of the clay, which also plays an important role in the swell behavior.

ACKNOWLEDGEMENTS

Authors would like to acknowledge National Science Foundation (Program Director: Dr. Richard J. Fragasz) for supporting this research under NSF Grant No.1031214. Any findings, conclusions, or recommendations expressed in the present material are those of the authors and do not necessarily reflect the views of NSF.

REFERENCES:

- Abduljawwad. (1993). "*Study on the performance of calcareous expansive clay.*" bulletin of the association of engineering geologists, vol. 30(4), pp. 481-498.
- Alonso, E.E., and Gens J.V. (1999). "*Modelling the mechanical behaviour of expansive clays.*" Engineering Geology, vol. 54, pp. 173-183.
- Al-Rawas A (1999) "The factors controlling the expansive nature of the soils and rocks of northern Oman". Engineering Geology, V 53, pp. 327–350
- Chen, F.H (1988). "*Foundations on expansive soils 2nd Ed.*" Elsevier Science Publications, New York.
- Chittoori, B. C. S, and Puppala, A. J. (2011). "*Quantitative estimation of clay mineralogy in fine-grained soils.*" *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 137(11), pp. 997-1008.
- Delage, P., Howat, M.D., Cui, Y.J. (1998). "*The relationship between suction and swelling properties in a heavily compacted unsaturated clay.*" Engineering Geology, vol. 50, pp. 31–48.
- Fredlund, D.G., and Morgenstern, N.R. (1996). "*Constitutive relations for volume change in unsaturated soils.*" Canadian Geotechnical Journal, Vol.13, pp. 261-276.
- Fredlund, D.G. and Xing, A. (1994). "*Equations for the soil water characteristic curve.*" Canadian Geotechnical Journal, vol. 31, pp. 521-532
- Holtz, W.G., and Gibbs, H.J. (1956). "*Engineering properties of expansive clays.*" Transactions of the American Society of Civil Engineers, vol. 121, pp. 641–663.
- Hussein E.A. (2001). "*Viscoplastic Finite Element Model for Expansive Soils.*" EJGE, paper 2001-0122.

- 1 Jones, D. E., and Holtz, W. J. (1973). “*Expansive soils: The hidden disaster.*” Civil Engineering,
2 New York, vol. 430(8), pp. 49-51.
- 3 Lambe, T.W., and Whitman, R.V. (1969). “ Soil mechanics - series in soil engineering” John
4 Wiley and Sons.
- 5 Mitchell, J.K., and Soga, K. (2005). “*Fundamentals of Soil Behavior.*” 3rd Edition, John Wiley
6 and Sons Inc., Hoboken, New Jersey.
- 7 O’Neill, M.W. and Poormoayed, N. (1980). “*Methodology for foundations on expansive soils*”
8 Journal of Geotech Eng. Div., ASCE 106 (GT12, December): 1345-1367.
- 9 Pedarla A. (2013) “SWCC and clay mineralogy based models for realistic simulation of swell
10 behavior of expansive soils” Dissertation submitted to the department of Civil Engineering,
11 University of Texas at Arlington, Tx.
- 12 Pedarla, A., Puppala, A.J., Hoyos, L.R., and Chittoori, B. (2015) “Evaluation of Swell Behavior
13 of Expansive clays from Internal Specific Surface and Pore Size Distribution”, ASCE Journal
14 of Geotechnical and Geoenvironmental Engineering. [http://dx.doi.org/10.1061/\(ASCE\)](http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0001412)
15 GT.1943-5606.0001412
- 16 Puppala, A.J., Katha, B., Hoyos, L.R. (2004). “Volumetric Shrinkage Strain Measurements in
17 Expansive Soils Using Digital Imaging Technology.” ASTM Geotechnical Testing Journal,
18 Vol. 27, No. 6, November, pp.547-556.
- 19 Puppala, A.J., Cerato, A. (2009) “Heave Distress Problems in Chemically-Treated Sulfate-Laden
20 Materials.” GeoStrata. Vol. 10, Issue 2, pp. 28-32.
- 21 Puppala, A.J., Manosuthkij, T., Nazarian, S., Hoyos, L.R., (2011) “Threshold Moisture Content
22 and Matric Suction Potentials in Expansive Clays Prior to Initiation of Cracking in
23 Pavements.” Canadian Geotechnical Journal, April, pp. 519-531.

1 Puppala A. J, Manosuthikij T. and Chittoori B.C.S (2013) "Swell and shrinkage characterizations
2 of unsaturated expansive clays from Texas" Engineering Geology, V164, pp.187-194.

3 Saiyouri, N., Tessier, D., and Hicher, P.Y. (2004). "*Experimental study of swelling in*
4 *unsaturated compacted clays.*" Clay Minerals, vol. 39, pp. 469–479.

5 Snethen, D.R. (1979). "An Evaluation of methodology for prediction and minimization of volume
6 change of expansive soils in highway subgrades." Research Report No. FHWA-RD-79-49.,
7 U. S. Army Eng. Waterway Exp. Sta., Vicksburg, MS.

8 Teresa, L.L., Hernández, J.B., Zaragosa, Cajun C. López. (2004). "Mineralogical
9 characterization of stabilized soils." Electronic journal of Geotechnical engineering, vol. 9F.

10 Yusuf, E., and Erol O. (2007). "*Swell pressure prediction by suction methods.*" Engineering
11 Geology, vol. 92, pp. 133–145.

12 Zhan, L., Chen, P., and NG C.W.W. (2007). "*Effect of suction change on water content and total*
13 *volume, of an expansive clay.*" Journal of Zhejiang University Science A, vol. 8(5), pp. 699-
14 706.

Figure 1: Schematic of 3-D swell strain test setup designed and manufactured at UTA

(a)

(b)

Figure 2: (a) 3-D swell chamber immersed in water tub (b) 3-D Swell test setup

Figure 3: 3-D Volumetric swell strain plot for Colorado soil specimen compacted at 95% MDUW and at different confinement levels

Figure 4: Measured SWCC for low plasticity clayey (CL) soil specimens compacted at 95% MDUW

Figure 5: Measured SWCC for high plasticity clayey (CH) soil specimens compacted at 95% MDUW

Figure 6: Variation of mechanical parameters of a soil specimen with swelling

Figure 7: Schematic for the measurement of slope of void ratio and logarithmic of matric suction

Figure 8: Behavior of Anthem soil specimen at 95% MDUW on e-w-log ψ plot

Figure 9: Behavior of test soil specimens at 95% MDUW on e-log ψ plot

Figure 10: 1 D Swell Strain MHC Model at 95% MDUW condition

Figure 11: MHC models for volumetric swell at different confinements for specimens compacted at 95% MDUW condition

Table 1: Basic soil classification and soil index properties

Soil	Liquid Limit	Plasticity Index (PI)	Specific Gravity G _s	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

Table 3: 3-D swell strains measured at different confining pressures

Ranking	Vertical strains (%)			Radial Strains (%)			Volumetric Strains (%)		
Soil	$\sigma = 7$ kPa	$\sigma = 50$ kPa	$\sigma = 100$ kPa	$\sigma = 7$ kPa	$\sigma = 50$ kPa	$\sigma = 100$ kPa	$\sigma = 7$ kPa	$\sigma = 50$ kPa	$\sigma = 100$ kPa
Grayson	9.11	6.40	5.60	1.26	1.18	1.03	11.65	8.76	7.67
Colorado	6.82	5.34	4.39	1.23	1.10	0.95	9.29	7.55	6.30
San Antonio	6.73	5.22	3.83	1.20	1.09	0.95	9.13	7.40	5.74
Burleson	5.78	4.58	3.07	1.12	0.93	0.80	8.03	6.45	4.69
Keller	4.75	3.96	2.07	1.04	0.88	0.82	6.84	5.73	3.71
Anthem	3.00	2.70	1.75	0.89	0.78	0.56	4.80	4.30	2.87
Oklahoma	3.20	2.16	1.63	0.91	0.76	0.53	5.03	3.69	2.69
San Diego	2.95	2.01	1.17	0.78	0.70	0.48	4.52	3.43	2.13

Table 4: Curve fitting parameters for SWCC models

Soil	Saturated volumetric moisture content (θ_{sat})(%)	Air entry value (ψ_a) (kPa)	Van Genuchten Model (1980)				Fredlund and Xing Model (1994)			
			a	n	m	R^2	a_1	n_1	m_1	R^2
Anthem	40.0	35.9	0.020	1.23	0.18	0.98	75	1.10	0.60	0.99
Burleson	50.0	74.5	0.005	1.55	0.35	0.98	210	1.45	0.90	0.99
Colorado	45.0	74.5	0.004	1.60	0.37	0.97	210	1.60	0.60	0.98
Grayson	50.1	65.0	0.010	1.65	0.39	0.98	110	1.50	0.90	0.99
Keller	26.0	20.0	0.010	1.70	0.41	0.98	110	1.50	0.85	0.98
Oklahoma	38.2	42.0	0.006	1.45	0.31	0.98	175	1.30	0.75	0.98
San Antonio	46.0	50.0	0.008	1.29	0.22	0.98	145	1.20	0.60	0.98
San Diego	37.5	50.0	0.008	1.29	0.22	0.98	170	1.10	0.60	0.98

Table 5: Calculation of MHCP from soil properties at 95% MDUW condition

Soil	Mechanical Hydro Parameter, α	Chemical Parameter, C	MHCP
Anthem	0.041	8.51	0.349
Burleson	0.078	16.76	1.308
Colorado	0.075	16.48	1.236
Grayson	0.151	22.72	3.431
Keller	0.070	7.48	0.524
Oklahoma	0.095	7.36	0.700
San Antonio	0.113	19.52	2.206
San Diego	0.011	6.36	0.070