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Evaluating the Ability of Swell Prediction Models to Predict the Swell Behavior of Excessively High Plastic Soils

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Abstract

Lightly loaded structures underneath expansive soils encounter severe damage due to the swell/shrink nature of expansive soils resulting from moisture variations. Billions of dollars are spent every year to repair the damages caused by these soils in the United States and worldwide. Designing structures to accommodate the swelling strains is a major challenge as predicting the swelling potential of these soils accurately is not easy. A wide variety of swell prediction models have been introduced by various researchers to predict the behavior of these often-problematic expansive soils. These models include various properties of soils such as, plasticity characteristics, compaction conditions, consolidation characteristics, moisture content variations, matric suction and clay mineralogical characteristics. However, these models are generally developed with typical moderate to high plastic soils in mind whose plasticity indices range from 25 to 45. Their applicability to soils that have liquid limits in the order of 200% is not well understood. In this paper, the ability of these models to predict the behavior of excessively high plastic soils with plasticity indices ranging from 45 to 85 were evaluated. For this purpose, four existing analytical prediction models that use combinations of above-mentioned properties were selected and used to predict the one-dimensional and three-dimensional swelling strains on three high swelling soils. These predictions were verified by conducting one-dimensional and three-dimensional swell tests on the three soil types. The swell tests were conducted at three different initial moisture contents to observe how well the models could predict different levels of moisture absorption. The ability of each of the four selected methods in predicting both 1-D and 3-D swell strains was discussed and their relative merits and demerits are highlighted. In addition, finite element modeling was performed to simulate one-dimensional and three-dimensional swell tests by using material models that use volumetric and suction changes with moisture contents to simulate expansive soil behavior within the finite element model. The results indicated that while the analytical prediction models gave reasonable results the finite element analysis predicted results were closest to the laboratory measure soils in case both 1-D and 3-D analyses. Among other analytical models the ones that incorporated mineralogical and suction data exhibited better results.

Introduction

The need for construction on expansive soils for infrastructural development possesses several challenges. Swell/shrink behavior of the expansive soils due to moisture variations/pore water pressure change induces considerable volume change – damaging the infrastructure built on them (Nelson and Miller 1992; Vu and Fredlund 2004). The distresses due to expansive soil causes higher financial loss than earthquake, floods, hurricanes, and tornadoes combined (Jones and Holtz 1973; Nelson and Miller 1992). The damage alone by expansive soil to the structures constructed on them in the US was reported to be $13 billion/year in 2009 (Puppala and Cerato 2009). Efficacy of stabilization techniques proposed for counteracting damages caused by expansive soils is contingent on the accuracy of prediction of swell pressure and soil heave over the design life of infrastructure (Vanapalli and Lu 2012).

Several correlations exist to predict soil movement as a function of soil state variables/index properties but soils used for validation of such model have plasticity index generally within 45 (Adem and Vanapalli 2013; Puppala et al. 2014, 2016; Vu and Fredlund 2004; Yilmaz 2006). However, in some areas, the plasticity index for these soils could be higher than 70. For example, expansive soils along highway US 95 along Idaho-Oregon border between mile posts 4.5 and 18.0 exhibited liquid limits in the range of 85 to 164 and plasticity indices ranging from 35 to 110 (Chittoori et al. 2016). Predicting the swelling capabilities of these types of soils is not straight forward using existing models as the swelling characteristics of these soils is beyond the range of values used to develop the current models. It is important to know which of the current models are versatile enough to capture the swelling behavior of these very high plastic clays. For this purpose, four models that differed in their approach to predict one-dimensional (1-D) and three-dimensional (3-D) swelling in expansive soils were selected for predicting the swelling behavior of three naturally occurring high swelling soils. This paper compares the applicability of each of these models in predicting swelling strains. Three different soils with varying plasticity indices were tested in this research. The input parameters required to predict the 1-D and 3-D swell for the respective models were determined from various laboratory tests conducted as part of this research. In addition to the analytical models, finite element modeling was performed to determine 1-D and 3-D swelling strains and compare these with a laboratory tested results. The comparison of predicted/simulated output with a laboratory tested data offers clarification of performance and applicability of the model for high plasticity clays.

Selected Analytical Models

This section describes the analytical models selected for this research. A brief description of the approach and its salient points are discussed here. The readers are encouraged to refer the original papers of these models for further details about them.

Puppala et al. (2016): This method predicts the swell behavior of expansive soils through Mechanical Hydro Chemical Parameter (MHCP) which is dependent on both matric suction and clay mineralogy. This framework combines unsaturated soil behavior with clay mineralogy using hydro-mechanical parameter (α) and chemical factor (C) factor respectively. The plasticity index values for the soils used in developing this framework ranged from 11 to 49.

Adem and Vanapalli (2013): This method is termed Modulus and Elasticity Based Model (MEBM). It is based off on simplification of the constitutive equation by Fredlund and Morgenstern (1977). The maximum potential heave which is a function of soil structure compressibility moduli, change in net normal pressure and change in matric suction as per Fredlund et al. (1980). The model was validated with Vu and Fredlund (2006) model which used Regina clay of PL 38%.

Vanapalli et al. (2010): Considering the limitations of time-consuming laboratory tests involved in the previous two methods, a simplified method proposed by Vanapalli et al. (2010) was selected. This method predicts soil swelling using both Fredlund (1983) and Hemberg & Nelson (1984) methods. In this method, three parameters, namely, corrected swelling index,Cs, suction modulus ratio, Cw, and correction parameter, K was used to determine the swelling potential. All the three parameters could be determined using empirical relations between plasticity and change in moisture content.

Yilmaz (2006): This is another simplified model that uses statistical analysis to predict the swelling in expansive soils. Multiple regression analysis was used on two major soil property, namely, liquid limit (LL) and cation exchange capacity (CEC) to predict swelling. It is well-known fact that LL and CEC are two influencing parameters that control volume change in expansive soils (Johnson and Snethen 1978; O'Neill and Ghazzaly 1977; Puppala et al. 2016; Weston 1980). The LL data ranged from 11 to 86, CEC ranged from 23 to 85 while the % 1-D swell ranged from 1 to 13 for the data points used in the multiple regression analysis.

Laboratory Testing

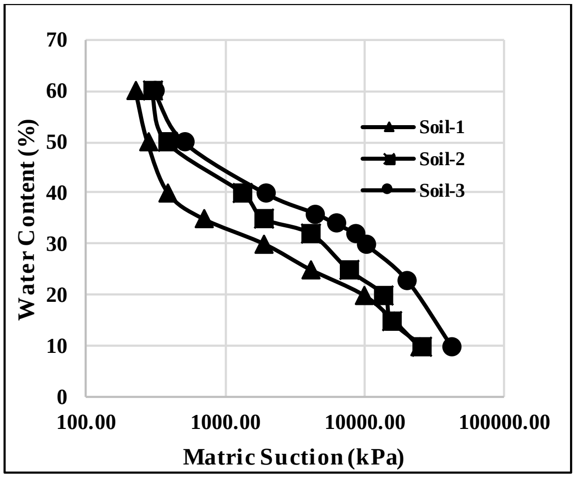
Laboratory testing was performed on the soil samples obtained from the distress locations along the US-95 highway. These soils were identified to have very high plasticity index values and exhibit high swelling pressures upon remolding (Hardcastle 2003, Chittoori et al 2016). The soil samples were collected between mile posts 4.5 and 18.0. Soil samples were named as Soil-1, Soil-2, and Soil-3 with increasing order of their plasticity indices.

Based on the input parameters required for the models selected in this paper, authors conducted several laboratory tests to determine the properties of the three selected soils. Tests such as Atterberg Limit test (ASTM D4318), Standard Proctor Compaction test (ASTM D698/AASTHO T99), Gradation of the soil (ASTM D6913), No. 200 Wash sieve (ASTM D1140-17), Hydrometer analysis (ASTM D7928-16e1) and 1-D swell test (ASTM D4546-96) were conducted to determine the physical properties of the soil. Tests were conducted as per the corresponding American Standards for Testing and Materials (ASTM) test procedure given in the brackets next to the test name in the previous sentence. In addition to these tests, Cation exchange capacity (CEC) and Specific surface area (SSA) test were conducted to determine the percentage of major clay minerals in the soils samples. CEC was determined based on Methylene blue index (MBI) of clay as per ASTM C837-09. SSA was measured using ethylene glycol monoethyl ether (EGME) method as per Cerato and Lutenegger (2002).The method suggested by Chittoori (2008) was used to determine the amount of major clay minerals in the soils. The soil properties determined after conducting the above-mentioned tests are given in Table 1. Additionally, authors also developed soil water characteristic curve (SWCC) to relate the water variation with matric suction data of the soil samples as per ASTM D 5298 (Filter Paper method). Whatman#42 ashless filter paper was used to determine the SWCC of the three soils tested in this research.

Table 1: Properties of the soil samples

Soil	**Soil-1**	**Soil-2**	**Soil-3**
Liquid Limit (%)	83	111	153
Plastic Limit (%)	41	40.4	66
Plasticity Index (%)	42	70.6	87
Maximum Dry Density (KN/m^3)	10.45	10.95	10.2
Optimum Moisture Content (%)	30%	32.6 %	29.6%
Clay Fraction (%)	64	69	82
1-D Swell Strain (%)	16%	17.9%	18.2 %
CEC(meq/100g)	110	120	130
SSA (m^2/g)	464.27	500.23	522.89

FIG 1 illustrates the water content and matric suction relationship of the three soils. Volumetric swell test as described by Chittoori (2008) was conducted to determine the 3-D dimensional swelling potential of the soil. Vertical and radial swell strains were monitored using strain gauge and PI tape respectively to determine the volumetric swell strain of the three soils. All tests were conducted at room temperature. Volumetric change (%) and the water content (%) relationship are given in FIG 2. Water content at the corresponding volumetric strain was determined by monitoring the weight of the sample with time; it was assumed that the change in weight of the sample is only due to the absorption of moisture.



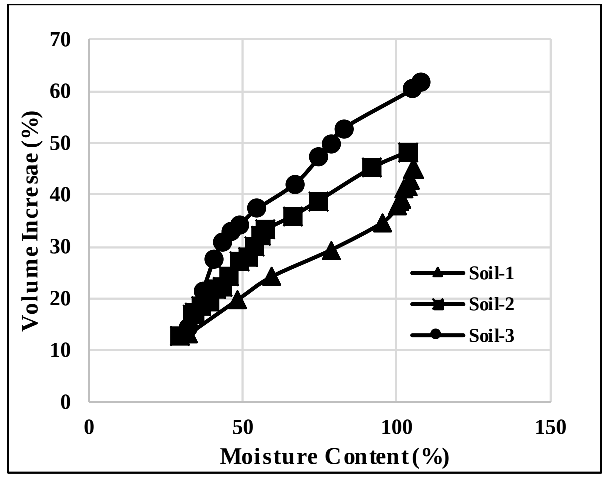


FIG 1 : SWCC of soil samples **FIG 2 : Volumetric swell results**

Prediction of Swell Strains

The soil properties determined from the laboratory testing were used in each of the models to predict the swelling strains of these soils. The following sections detail the steps involved in predicting the swelling strains for each of the model along with the final result obtained from the model.

Swell Prediction Using MHCP:

This model requires that the clay minerals be quantified in the clay fraction and change of void ratio with matric suction of the soil. Since, montmorillonite, kaolinite, and illite are the most common clay minerals (Mitchell and Soga 2005), these clay minerals were quantified using the CEC and SSA as per Chittoori (2008) and the results are tabulated in Table 2. The swell fraction (SF) as defined by Puppala et al. (2016) for montmorillonite(M) - SF_1, illite (I)- SF_2 and kaolinite (K) - SF_3 was taken to be 90, 9, and 1 respectively based on their individual double diffuse layer thickness for a crystal of 1 Å where total contribution was taken to be 100 (Mitchell and Soga 2005; Puppala et al. 2016). The clay fraction (CF) was determined from particle size analysis as per ASTM D422. Chemical factor (C) is presented in Table 3 which is a function of clay fraction (CF), swell factor (SF) and particular mineral fraction in clay (f_i) and was determined as per equation (1). The hydro-mechanical factor (α) for each soil listed in Table 4 was determined from the slope of idealized matric suction and void ratio plot during the swelling process. The computation of MHCP parameter was done using equation (2) and respective swells were computed using equation (3) and equation (4). The results are tabulated in Table 4.

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

$$\text{MHCP} = \pi(\alpha, C) \qquad (2)$$

$$\epsilon_{1\text{-D, Swell}} = 6.12 \text{ x MHCP}^{0.263} \qquad (R^2=0.73) \qquad (3)$$

$$\epsilon_{3\text{-D, 7kPa}} = 7.53 \text{ x MHCP}^{0.25} \qquad (R^2=0.77) \qquad (4)$$

Table 2: CEC, SSA, and mineral composition

Soil	CEC (meq/ 100 g)	SSA (m^2/g)	% M (f_1)	% I (f_2)	% K (f_3)
Soil-1	110	464.27	72.61	20.58	6.800
Soil-2	120	500.23	78.73	17.50	3.76
Soil-3	130	522.89	83.25	14.16	2.60

Table 3: Chemical Factor Calculation

Soil	C (1)	CF (2)	SF_1 x f_1 (3)	SF_2 x f_2 (4)	SF_3 x f_3 (5)	Sum (3 to 5)
Soil-1	43.05	64	65.35	1.85	0.07	67.27
Soil-2	50.00	69	70.85	1.57	0.04	72.46
Soil-3	62.50	82	74.922	1.27	0.03	76.22

Table 4: 1-D and 3-D swell prediction using MHCP model

Soil	α	C	MHCP (α x C)	$\epsilon_{1\text{-}D}$ (%)	$\epsilon_{3\text{-}D,\ 7kPa}$ (%)
Soil-1	0.47163	43.05	20.30	13.51	15.98
Soil-2	0.44728	50.00	22.36	13.86	16.38
Soil-3	0.42928	62.50	26.83	14.54	17.14

Swell Prediction Using MEBM

Change in matric suction, elastic moduli with respect to change in matric suction and poison's ratio was used to calculate 1-D heave. The change in matric suction ($\Delta\Psi$) was calculated from the difference of final matric suction after swelling has occurred (Ψ_{final}) and initial matric suction at the start of the test ($\Psi_{initial}$). The change in void ratio with change in net normal stress was measured from 1-D consolidation test for calculation of saturated Young's modulus of elasticity(E_{sat}) as per Zhang (2004). The parameters β and α are fitting parameters which were taken as 2 and 0.1 respectively and Poisson's ratio(μ) as 0.4 in accordance to Vanapalli and Oh (2010). These parameters were used to calculate E_{unsat} at the end of full swell. The value of E_{unsat} was used for calculation of elastic modulus (H) with respect to final matric suction (Ψ_{final}). Strain was calculated as per equation (5). The values obtained are listed in Table 5.

$$\varepsilon_y = m_2^s.(\Psi_{\text{final}} - \Psi_{\text{initial}}) \text{ where } m_2^s = (1 + \mu/H(1-\mu)) \quad (6)$$

Table 5: Calculation of parameters for MEBM

Soil	$\Delta\Psi = \Psi_{final} - \Psi_{initial}$ (kPa)	E_{unsat} (kPa)	$\frac{\Delta e}{\Delta\Psi}$	e_0	H (kPa)	m_2^s	ε_y(%)
Soil-1	1556.50	13855.77	0.0019	1.78	69278.86	3.37E-05	5.24
Soil-2	3731.31	17937.89	0.0025	1.98	89689.45	2.60E-05	9.71
Soil-3	9342.53	39593.31	0.0023	2.12	197966.55	1.18E-05	11.01

Swell Prediction Using Vanapalli et al. (2010):

Model from Vanapalli et al. (2010) is used to predict 1-D swell for given soil with their plasticity indices and variation of water content. All the soils have plasticity index more than 30, so that the empirical correlations are used to find the parameters for the model. In this empirical correlation, three parameters, namely, corrected swelling index (C_s), suction modulus ratio (C_w), and correction parameter (K) were used to determine the swelling potential. P_f represents the final stress state. Model parameters for the given soils are tabulated in Table 6. It was found that the predicted swell is close to the swell found from 1-D swell test except for Soil-1 soil.

Table 6 Swell prediction using Vanapalli et al. (2010) method

Soil	PI (%)	C_w	C_s	K_I	K_{II}	P_f (kPa)	ΔH (in) (using K_I)	ΔH (in) (using K_{II})
Soil-1	42	0.024	8.2E-2	3.6E-3	4.3E-3	7	0.0560	0.0534
Soil-2	71	0.024	2.2E-1	2.6E-3	4.4E-3	7	0.1536	0.134
Soil-3	87	0.024	3.8E-1	2.2E-3	4.4E-3	7	0.2635	0.2204

<u>Swell Prediction Using Yilmaz (2006):</u>

The statistical model proposed by Yilmaz (2006) was used to predict the swell for three soils with the corresponding liquid limit (LL) and cation exchange capacity (CEC) values . Multiple regression analysis was used for the LL and CEC for the soil samples. It was found that the predicted swell is close to the swell strains found from 1-D swell test from the lab which is shown in Table 7.

Table 7 Swell prediction using Yilmaz (2006) method

Soil	LL (%)	CEC (meq/100g)	1-D Swell (%)
Soil-1	83	110	9.98
Soil-2	111	120	14.25
Soil-3	153	130	20.68

<u>Finite Element Model Predictions:</u>

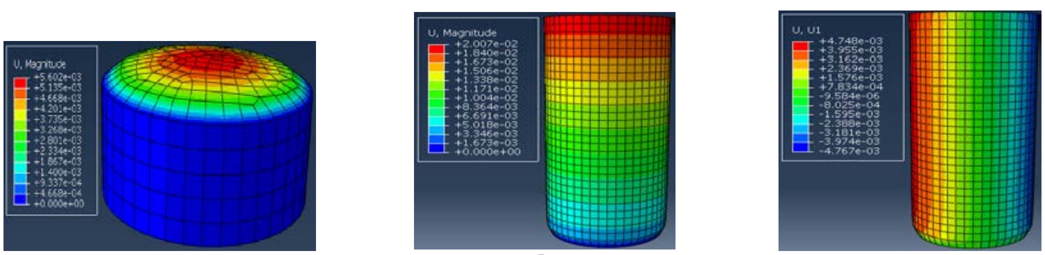
A finite element software, ABAQUS® was used in this research as it was promising to replicate the realistic behavior of complex problems due its versatile built in material models including the application in transportation engineering (Helwany 2007, Puppala et al. 2014). Simulation of expansive soils is especially tricky, since both volume change and strength behavioral changes with respect to moisture fluctuations need to be accounted for accurate predictions. ABAQUS®, has built-in material models that can be used to simulate shrink and swell behaviors of expansive soils by accounting for moisture content and suction related changes. The moisture swelling model assumes that the volumetric swelling of the porous medium's solid skeleton is a function of the saturation of the wetting liquid in partially saturated flow conditions (Dassault Systèmes Simulia Corp. 2016). In case of partially saturated condition, an initial saturation value and a consistent pore fluid pressure need to be defined for the analysis which must be lies within the absorption/exsorption values for that saturation value. On the other hand, sorption model is used to illustrate the absorption/exsorption behavior of the porous element under partially saturated conditions. This model is used for coupled wetting liquid flow and porous medium stress analysis in the porous medium. In partially saturated condition, negative pore liquid pressure defines the capillary effect in the medium which represents the absorption/exsorption condition of that medium. The absorption/exsorption behavior is also a function of saturation. These two models can only be used for the elements that allow pore pressure. Using these two models, one could successfully simulate volume change behavior of expansive soils with moisture variation in finite element framework. These two models were used in this research to simulate expansive soil behavior.

The required data for each of the soils was determined during the laboratory testing phase of this research. The moisture content vs suction data (FIG 1) was used as input data for sorption model which replicates the soil suction change with respect to moisture content. The volumetric swell vs moisture content data obtained from 3-D swell test (FIG 2) was used as input to sorption model. Saturation values and the corresponding moisture contents were input into the FEM analysis. The material properties used to model expansive soils for both 1-D and 3-D cases are presented in Table 8. Optimum moisture content and maximum dry density corresponding to the initial saturation were input as initial conditions in the analysis. Two types of boundary conditions (BC) were utilized in this study: displacement BC and pore water pressure BC. The displacement BCs were used to identify the free and fixed directions for the model movement while pore water pressure BC was used to specify a source of water for the expansive soil. Bottom and the outside radius of the soil were restricted in all direction and water BC was at the top and bottom of the soil to replicate the 1-D swell condition.

Meshing criteria is one of the most important features in finite element analysis. The results of analysis can change significantly due to the element's type and size. 0.005 m element size and 8-noded brick with trilinear displacement and trilinear pore pressure (C3D8P) element type were used for the 1-D and 3-D analysis to allow pore pressure in the system. A 7 kPa of pre-loading condition was used at the top of the soil to replicate the 1-D swell condition in the lab. FIG 3 (a) illustrates the 1-D swelling result of soil-3 from numerical analysis. In case of 3-D volumetric swell, bottom BC was restricted to all directions and water BC was applied at the top and bottom of the soil. A confining pressure of 7kPa was applied at the outer perimeter of the soil. In both cases, soil samples have reached full saturation conditions. FIG 3 (b) and FIG 3 (c) shows the vertical and radial swell test result of soil-3 from numerical analysis. Both 1-D and 3-D swell test results from the numerical analysis exhibit the similar trend compared to laboratory results. However, numerical results are a bit higher than the lab results. Table 9 exhibits a brief detail of 1-D and 3-D swell test results using numerical analysis.

Table 8 Engineering properties of soil used in the model

Soil	Soil-1	Soil-2	Soil-3
Mass Density, ρ (kg/m³)	1045	1095	1020
Elastic Modulus, E (kPa)	13855	17937	39593
Poisson's Ratio	0.4	0.4	0.4
Cohesion, c (kPa)	46	60	131
Angle of Friction, ϕ(°)	26	23.5	21
Angle of Dilation, ψ (°)	8.5	7.8	7
Initial Void Ratio, e_o	1.39	1.52	1.64
Initial Saturation, S_0 (%)	61	56	53
Permeability, k (m/s)	1E-9	1E-9	1E-9



(a) **(b)** **(c)**

FIG 3: Results from numerical analysis for Soil-1 (a) 1-D vertical swell (b) 3-D vertical Swell (c) 3-D radial Swell

Table 9 Swell Prediction using numerical analysis

Case	Soil	Soil-1	Soil-2	Soil-3
1-D	Initial Thickness of the soil, Hi (m)	0.0254	0.0254	0.0254
	Vertical Displacement, ΔH (m)	4.3E-3	5.23E-3	5.6E-3
	% Vertical Swell	16.9	20.5	22
3-D	Initial Thickness of the soil, Hi (m)	0.1524	0.1524	0.1524
	Initial Radius of the soil, Ri (m)	0.0381	0.0381	0.0381
	Vertical Displacement, ΔH (m)	1.56E-2	1.85E-2	2.01E-2
	Radial Displacement, ΔR (m)	3.4E-3	4.37E-3	4.74E-3
	% Volumetric Swell	31.04	38.1	42.8

Discussion

FIG 4 presents a comparison of 1-D swell strains among all prediction models with the laboratory data. It can be observed from this figure that all prediction models predicted lower swell strains for lower PI soil and higher swell strains for higher PI soil; although the exact magnitude was different the trends were accurate. A similar plot was made for 3-D swell strains for the two predictions and the laboratory data. Both 1-D and 3-D swell strains predicted by the MHCP model were less than the laboratory results however, the difference in predicted swell strains was minimal among the three soils similar to the laboratory measure data. Higher amount of discrepancy could be observed for 3-D swell prediction than 1-D. A potential reason for such discrepancy with laboratory swell value was attributed to use the of moderated plasticity soil (PI <45) in coming up with regression equation for MHCP model. The prediction of the model for Soil-1 - low plasticity clay, had small discrepancy in comparison two other two soils. The amount of discrepancy was found to be proportional to PI.

The parameters E_{unsat} required by MEBM, which is the function of matric suction, was calculated at end of swelling. The 1-D swell predicted using MEBM \and observed in laboratory had similar trend but amount of swell value predicted by the model was substantially less in comparison to the laboratory value and value from MHCP model as shown in FIG 4. These discrepancies could be attributed to the lack of consideration of soil mineralogical properties which have significant effect on the swelling behavior. The higher difference between the swell predicted between MHCP and MEBM in Soil-1 in comparison to Soil-2 and Soil-3 was observed which could be due to higher influence of chemical parameters in swelling than hydro-mechanical for this particular soil.

Both Vanapalli et al. (2010) and Yilmaz (2006) model show increasing trend of % swell with the increase of plasticity index which is shown in FIG 4. However, the amount of swell from both model provide lower value for soil-1 and soil-2 and higher value for soil-3. The cause of the inconsistency of these models could be the absence of suction property consideration. Additionally, Vanapalli et al. (2010) did not consider mineralogical properties of the soil which may differ the results. Both model exhibit higher prediction for soil-3. Prime reason for this behavior could be the high LL and PI value of soil-3. Vanapalli et al. (2010) empirical model considered for PI<80 whereas Yilmaz (2006) regression model formulated for LL<90.

Numerical analysis result from ABAQUS® shows most consistent prediction for both 1-D and 3-D swell compared with other swell prediction models which are shown in FIG 4 and FIG 5 respectively. Swell phenomenon was predicted using moisture swelling and sorption model which accommodated actual suction change as well as volume change with moisture variation. However, swell prediction was a bit higher for all cases.

In order to better visualize the differences in the swell predictions the difference between predicted and laboratory swell strains was plotted for all the predictions. This data is presented in FIG 6. It can be observed from this figure that the finite element model was most accurate in predicting the swelling strains. The next best model as per this data is the MHCP model. Both the remaining three models, MEBM, Vanapalli et al. (2010) and Yilmaz (2006), either over predict or under predict the 1-D swell strain by 4 to 11 percent.

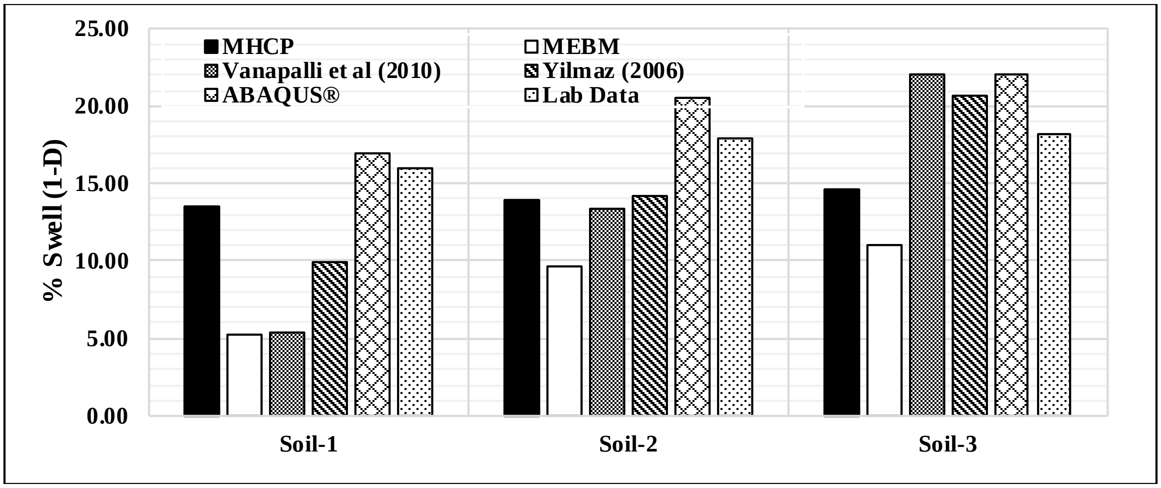


FIG 4: Comparison of 1-D swell results for all three soils

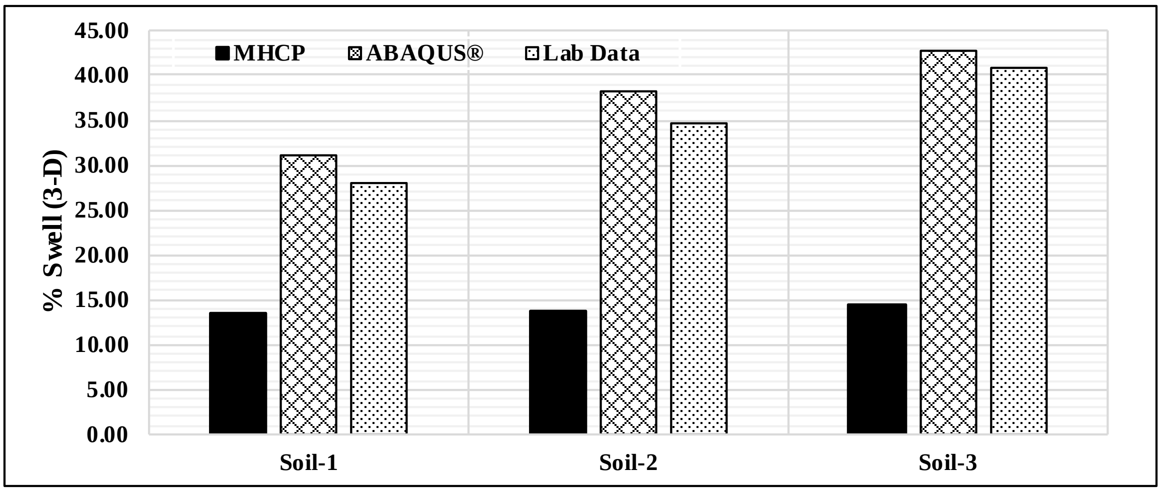


FIG 5:Comparison of 3-D swell results for all three soils

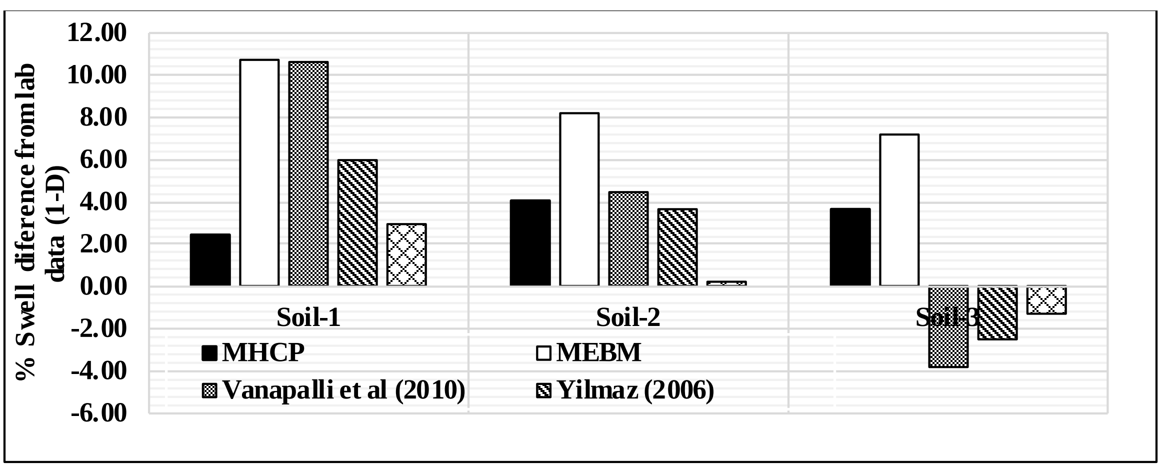


FIG 6: Percentage swell difference between the prediction and the measured laboratory data for all three soils

Summary

Four analytical swell prediction models which were developed for medium PI soils were used to predict 1-D and 3-D swell strains for three different types of soil with high PI values. The results from the analytical models were compared with the laboratory data. Considerable amount of accuracy was observed in heave prediction by the selected models.

Although the model that incorporates soil mineralogy and matric suction had better accuracy in prediction of the heave than the model that considers only the role of matric suction, finite element model was the most consistent in predicting 1-D and 3-D swell strain which considers suction change as well as volume change with moisture variation.

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