A simple approach for predicting vertical movements of expansive soils using the mechanics of unsaturated soils

Une approche simple pour prédire les mouvements verticaux des sols gonflants par la mécanique des sols non saturés

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ABSTRACT: The vertical soil movements associated with environmental changes which include climate, vegetation, watering of lawn and soil cover type for a test site with an expansive soil deposit in Regina, Canada were predicted by Ito and Hu (2011) using a combination of soil-atmosphere and soil-displacement models for a period of one year. In this paper, vertical soil movements of the same site were estimated reasonably well considering soil suction changes and associated modulus of elasticity as key parameters in a volume change constitutive relationship that is based on the mechanics of unsaturated soils. The proposed method is referred to as the modulus of elasticity based method (MEBM). The MEBM has been also evaluated earlier for three other case studies with satisfactory results. The results of the study presented in this paper and the other three case studies that were reported in the literature are encouraging for extending the simple MEBM in engineering practice for rational design purposes of both the sub and superstructures constructed in or on expansive soils.

RÉSUMÉ: Les mouvements verticaux des sols associés aux changements environnementaux qui comprennent le climat, la végétation, l'arrosage de la pelouse et le type de couverture du sol pour un site d'essai avec un dépôt de sol gonflant à Regina, Canada ont été prédits par Ito et Hu (2011) en utilisant une combinaison de modèles sol-atmosphère et de déplacement du sol pour une période d'un an. Dans cet article, les mouvements de sol verticaux sur le même site ont été estimés raisonnablement bien en tenant compte de la succion dans le sol et du module d'élasticité associés comme paramètres clés pour une relation constitutive du changement de volume qui est basée sur la mécanique des sols non saturés. La méthode proposée est appelée méthode basée sur le module d'élasticité (MBME). La MBME a également été évaluée précédemment pour trois autres études de cas avec des résultats satisfaisants. Les résultats de l'étude présentée dans ce document ainsi que les trois autres études de cas qui ont été rapportés dans la littérature sont encourageants pour l'application de la MBME pour la conception rationnelle tant des substructures que des superstructures construites dans ou sur les sols gonflants.

KEYWORDS: unsaturated expansive soils, vertical movement, suction, modulus of elasticity, vegetation, climate.

1 INTRODUCTION

Expansive soils shrink and swell in response to alternate dry and wet conditions inducing vertical soil movements. These soil movements cause significant damage to the lightly loaded engineered structures and contribute to economic losses which are greater than all natural disasters combined (Jones and Holtz 1973). The behavior of expansive soils associated with environmental changes hence should be considered when designing buildings, pavements, foundations (shallow and deep), pipelines, retaining walls, earth dams, canal or reservoir linings, and other structures that are constructed in or on expansive soils.

Different methods for predicting the volume change behaviour of expansive soils have been proposed in the literature. However, most of the available methods focused on predicting the maximum potential heave at saturation condition. Furthermore, these methods or studies were limited to expansive soils of local regions that cannot be extended universally. Recently, Vanapalli and Adem (2012, 2013), and Adem and Vanapalli (2013) presented and assessed a simple approach for estimating the vertical soil movements of different expansive soils for overcoming these limitations. In this approach, the volume change constitutive relationship developed by Fredlund and Morgenstern (1976) for unsaturated soils was integrated along with the soil-atmosphere model VADOSE/W (Geo-Slope 2007). The analyses of the results demonstrated that the proposed approach, which has been referred to as the Modulus of Elasticity Based Method (MEBM), was capable of reproducing the vertical movement of expansive soils over time in response to the net changes in soil suction within the active zone for three different case studies (Vanapalli and Adem 2012, 2013, and Adem and Vanapalli 2013).

The objective of the present study is to check the validity of the MEBM for an additional test site with an expansive soil deposit in Regina, Saskatchewan, Canada. This site was originally modeled and presented by Ito and Hu (2011). These investigators simulated the Regina expansive clay vertical movements based on the suction data predicted from the soil-atmosphere coupled model by applying one year's climate data (from 1 May, 2009 to 30 April, 2010). The liquid limit and plastic index values of Regina clay vary from 70 to 94% and from 40 to 65%, respectively. The soil properties required include the soil water characteristic curve (SWCC) and the coefficient of permeability function along with the climate and vegetation data as input for the soil-atmosphere model. The vertical movements of this soil with respect to the changes in suction values were predicted using the soil-displacement model. A general purpose partial differential equation solver (FlexPDE) was used as a tool to solve the governing partial differential equations in the modelling process. Various factors that influence the soil movements such as the climate, vegetation, watering of lawn and soil cover type were considered in the modelling.

In this paper, estimated values of soil suction, volumetric water content and vertical movements of expansive soils at different depths obtained from the MEBM were compared with the published results of Ito and Hu (2011). Due to limitations of space, only the results of soil suctions and vertical movements have been presented and discussed in this paper, in addition to providing comparisons with the results of Ito and Hu (2011). There is a good comparison between the results from both the studies.

2 BACKGROUND

2.1 The constitutive relationship for estimating the vertical movements of expansive soils

The volume change behavior of any expansive soil deposit relative to the changes in site conditions can be rationally interpreted by extending continuum mechanics principles in terms of two independent stress state variables of unsaturated soils; namely, matric suction $(u_a - u_w)$, and net normal stress $(\sigma - u_a)$ (where, u_a = the pore-air pressure, u_w = the pore-water pressure, and σ = the total stress). Water movement into / out of an unsaturated expansive soil leads to a change in suction and contributes to soil volume change predominantly in the vertical direction (i.e., the soil lateral deformations are negligible). In other words, the K_0-loading was assumed in the present study. In the MEBM, the incremental vertical movement, dh, was related to changes in matric suction neglecting the limited influence of the net normal stress within the surficial active zone as follows:

$$dh = m_2^s \, d(u_a - u_w) \tag{1}$$

where, $m_2^s = (1+\mu)/(H(\mu-1))$ = the soil structure compressibility modulus associated with a change in suction $(u_a - u_w)$ (where H = elasticity modulus with respect to change in suction and μ = Poisson's ratio).

To calculate the vertical soil movement for a given site, the soil within the active zone was divided into n layers. The vertical movement for each layer, Δh_i, was computed by multiplying the incremental vertical movement at the mid-layer (Equation 1) and the layer thickness, h_i. The total vertical movement for the soil profile, Δh, was then calculated by adding the vertical movement of all layers within the active zone.

$$\Delta h = \sum_{i=1}^{n} \Delta h_i = \sum_{i=1}^{n} \left(h_i \left[m_2^s \, d(u_a - u_w) \right]_i \right) \tag{2}$$

Oh et al. 2009 studies show that the value of the modulus of elasticity with respect to change in net normal stress, E, varies significantly with soil suction. In the proposed MEBM, the semi-empirical model introduced by Vanapalli and Oh (2010) was used to estimate the modulus of elasticity, E, associated with any value of the soil suction.

$$E_{unsat} = E_{sat} \left[1 + \alpha \frac{(u_a - u_w)}{(P_a/101.3)} (S)^{\beta} \right] \tag{3}$$

where E_{unsat} and E_{sat} = the soil moduli of elasticity under unsaturated and saturated conditions, respectively, P_a = atmospheric pressure (i.e., 101.3 kPa), S = degree of saturation, and α and β = the fitting parameters.

To calculate the soil structure compressibility modulus, m_2^s, the modulus of elasticity with respect to change in suction, H, was estimated using the relationship below:

$$H = E / (1 - 2\mu) \tag{4}$$

The relationship between H and E may be more complex for soils in a state of unsaturated condition; however, this relationship which is valid for saturated soils has been extended for unsaturated soils in the present study. Similar assumptions were suggested by Geo-Slope International Ltd. for modeling soil heave due to infiltration using SIGMA/W.

2.2 VADOSE/W for estimating the changes in soil suction

Estimation of soil suction changes due to soil water migration (infiltration/evaporation) in the active zone is important in predicting the vertical movement of expansive soils. The computer program VADOSE/W, a product of Geo-studio, was used as a tool to estimate the net changes in soil suction with respect to time and depth (Geo-Slope 2007). The program couples the flow of water, heat and vapor through both saturated and unsaturated soils to provide a direct evaluation of soil water storage and suction. Critical to the formulation of VADOSE/W is its ability to predict actual evaporation as a function of climate data, applied as an upper boundary condition, using the rigorous Penman-Wilson method (Wilson, 1990).

The input parameters required for VADOSE/W include soil properties such as the SWCC and the coefficient of permeability function, climate and vegetation data. The climate data include the daily precipitation, the maximum and minimum daily temperature, the maximum and minimum daily relative humidity, the average daily wind speed and net radiation. The vegetation data include the leaf area index (LAI), the plant moisture limiting point, the root depth and the length of the growing season.

The output from VADOSE/W includes modeled data such as temperature, evaporation, suction, and volumetric water content. In the present study, only the modeling results for soil suctions versus time are presented and compared with the published data of Ito and Hu (2011).

3 CASE STUDY: REGINA EXPANSIVE CLAY (ITO AND HU 2011)

The city of Regina, SK, Canada is located on highly expansive clay deposits that exhibit large volume changes as the soil moisture changes. Failures in light infrastructures buried in the soil have increased greatly in recent years, especially in older areas with asbestos cement (AC) water mains (Hu et al. 2008). As a part of a program of study the performance of AC water mains in Regina expansive clay, Ito and Hu (2011) modeled a site located in a residential area with a high water main breakage rate. It includes a park area with thick grass of 100 mm and a wide paved road with 150 mm thick asphalt pavement. Infiltration due to precipitation and park watering and evapotranspiration from the grass were considered to model the soil suction fluctuations for this site.

The results from the Regina test site were used to validate the proposed MEBM in estimating the vertical soil movements over time considering the field condition (vegetated park area and asphalt-paved area). The stratigraphy of the site consists of approximately 6.4 m of highly plastic clay, 1.8 m of elastic silt and 6.8 m of till as shown in Figure 1. The choice of thickness and soil properties for each layer was guided by field observations made by Vu et al. (2007). The climate data obtained from a weather station at the Regina international airport was applied at the vegetative cover over a period of one year (from 1 May, 2009 to 30 April, 2010). Figures 2 and 3 show the SWCCs and the coefficient of permeability functions, respectively, for Regina and other materials used in the numerical modelling. Ito and Hu (2011) provide more details about the soil, the climate, and the vegetation data of the site.

4 RESULTS AND DISCUSSIONS

4.1 Estimation of the soil suctions

The soil profile shown in Figure 1 was modeled using the fully coupled transient analysis with the 2-D software package (VADOSE/W) to estimate the suction changes associated with the environmental changes for a period of one year. Beside the soil properties, the initial and boundary conditions are needed as input data to run the program. The initial conditions for all nodes of the model domain, including pressure and temperature, were derived from implementing a steady-state analysis using the same model. Based on the field suction data measured by Vu et al. (2007), the initial pressure head during the steady-state analysis was set up to be -163.15 m for the top 3 m of the clay layer, -101.97 m for the rest of the clay, -61.18 m for the silt, and -203.94 m for the till. The temperatures of nodes at the lower boundary were set up to be 10 °C.

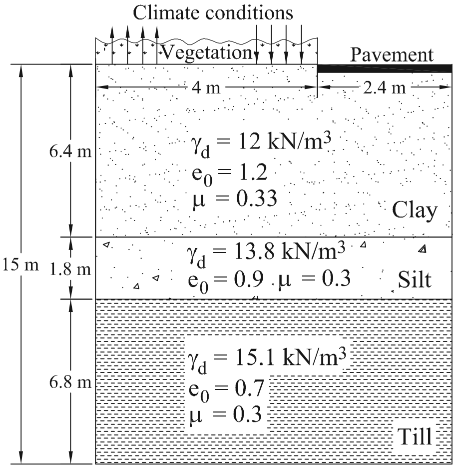


Figure 1. Soil profile and soil properties (Ito and Hu 2011)

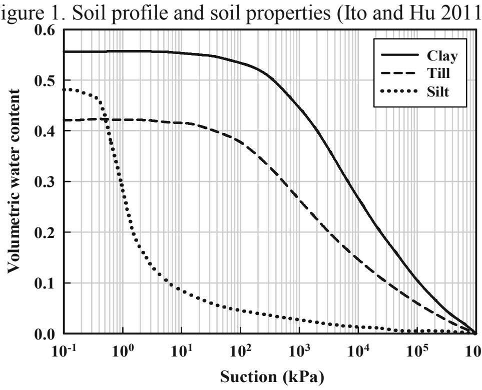


Figure 2. Soil-water characteristic curves (Ito and Hu 2011)

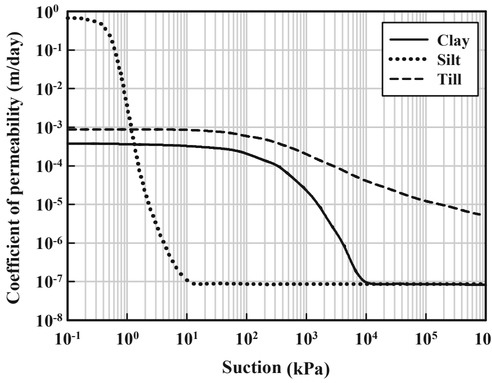


Figure 3. Coefficient of permeability functions (Ito and Hu 2011)

The climate and the vegetation data for the period of study were applied during the fully coupled transient analysis on the vegetated area only. A "no flow" natural boundary condition was applied in VADOSE/W by default on the pavement to represent the pavement as an impervious layer and moisture in and out flow are occurring through the vegetated area (see Figure 1). In winter season (1 November, 2009 to 31 March, 2010), the precipitation was received as snow. The cumulative snow precipitation was applied on a single day, when the temperature rose and remained above 0 °C (1 April, 2010). The climate data recorded at the Regina Airport weather station was used for the modeling. The climate in winter months was however set up to be constant. The temperature was assumed to be -5^{o}C, the relative humidity as 100%, and the remainder of the climate data was zero. In other words, the model was not intended to simulate soil movement activities during winter.

Because the site is located in a residential area with a park that has mature trees, the daily wind speed, precipitation and net radiation recorded at the weather station were multiplied by scale factors of 0.3, 0.7, and 0.3, respectively, as suggested by Ito and Hu 2011. Furthermore, a park watering rate of 1.8064 × 10^{-3} m/day was applied on every Monday and Friday for the period from 23 June to 12 October as reported in Vu et al. 2007. However, water uptake by mature trees was not included in the modeling.

Similar to Ito and Hu 2011, and Vu et al. 2007, the vegetation was specified as good grass and the growing season was assumed to start in April and end in October as suggested by Vu et al. (2007). The LAI function for good vegetation with a maximum LAI value of 2 was used as suggested in SoilCover (Unsaturated Soils Group 1996). The root depth of 150 mm was used as suggested and the root distribution was assumed to be triangular. A plant moisture limiting point of 500 kPa and a wilting point of 2500 kPa were used for this simulation.

Mass balance checking was performed on the VADOSE/W run, and the model solved with a total mass balance error of less than 1.5%.

Figure 4 shows the predicted soil suction response to a changing surface boundary over the entire year under the centre of the vegetation cover. The soil suction was found to vary with depth and time. It can be seen that the fluctuations in suctions correlated well with the environmental conditions on the surface boundary. The suction at the ground surface fluctuated widely and these fluctuations reduced with depth. The predicted suctions for this study agreed well with the results of Ito and Hu (2011). The correspondence between the suction values was accomplished using the same meteorological data (e.g., precipitation, temperature), soils properties and initial boundary conditions.

The corresponding suction profiles under the centre of the vegetation cover for various times were also investigated. However, due to limitations of the paper length, suction profiles are not provided in this paper. In general, extreme changes in suction (that vary between 600 and 2500 kPa) occurred at the ground surface. The suction values are typically greater at the surface during relatively dry periods. During infiltration, the suction values decreased at the surface, and it continued to decrease further as water infiltrated to greater depths. The suction fluctuations were predominant at the surface and approached minimum values at 3.4 m (which is the active zone depth). According to Azam and Ito (2012), this behavior was attributed to the surface soil layer that was initially at an unsaturated state and imbibed any water available by the infiltration. Likewise, the layer can rapidly lose water under relatively dry conditions. With increasing depth, the overlaying soil provides a cover and the geotechnical properties of the underlying materials become progressively more significant. The high water retention capability and the low coefficient of permeability of the Regina clay, especially under unsaturated conditions, impede the soil suction at higher depths to respond to the variations of the surface boundary. This soil-atmospheric interaction corroborated well with the suction values obtained from Ito and Hu (2011) thereby validating the VADOSE/W output that can be used for predicting the vertical movement of the test site with Regina expansive clay.

4.2 *Estimation of the vertical soil movements*

To calculate the vertical soil movements at different depths (0, 0.5, 1, 2, 3, and 6 m), the soil profile was divided into several sub-layers up to 6.4 m depth (which is the thickness of Regina expansive clay layer). The total vertical movement of the soil at a certain depth for a given day was computed by adding the vertical movements of all layers up to the considered depth using Equation 2. The soil compressibility modulus, m_2^s, was calculated using the Poisson's ratio (μ = 0.33) and the soil modulus of elasticity in terms of soil suction which was calculated using Equations 3 and 4. Vanapalli and Oh (2010) suggested the fitting parameter, β, equals 2 for fine-grained soil, which was used for Regina expansive clay. The fitting parameter, α, was assumed to be 1/12 in order to provide reasonable comparison between the predicted and the published results of the vertical soil movements. The modulus of elasticity under saturated condition, E_{sat} = 750 kPa, was suggested based on the results of the conventional oedometer tests conducted by Vu (2003) on Regina expansive clay. The soil movement was predicted as a function of time and depth. Due to limitations of space, the soil movement variations are not provided in this paper. Both shrink and swell behavior were observed in the period of the study. The vertical soil movement has a strong correlation with the predicted suction values. As anticipated, no vertical movement of the soil was observed below the active zone. The vertical soil movements estimated in this study were in reasonable agreement with the results of Ito and Hu (2011), clearly responding to climatic trends and infiltration events. Figure 5 provides a comparison between the vertical soil movements estimated using the MEBM and Ito and Hu (2011) method at different depths and times. The agreement between the results of two methods is reasonable. Some differences observed can be attributed to the differences in predicted soil suction profiles using different methods. This may be also due to the governing equations which were different for both the methods used for estimating the vertical movement.

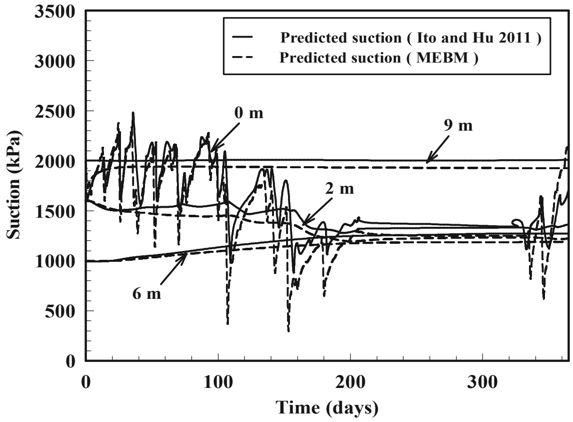
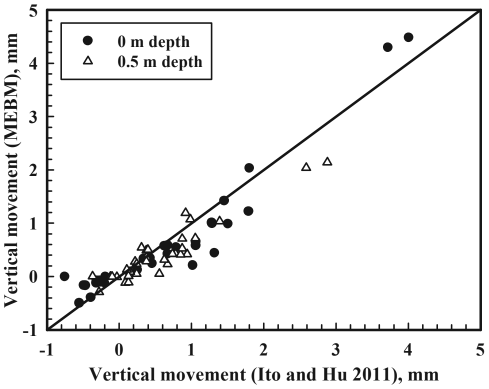


Figure 4. Soil suction changes with respect to time and depth

Figure 5. Comparison of the vertical soil movement estimated using the



MEBM and Ito and Ho (2011) method

5 CONCLUSIONS

Verification of the Modulus of Elasticity Based Method (MEBM) for predicting the vertical soil movements over time was accomplished in this paper using the numerical modeling results of Ito and Hu (2011) for a Regina test site for a period of one year. The changes in suctions due to alternate dry and wet conditions were estimated using VADSOE/W. The soil movements induced by the changes in suction were calculated using the volume change constitutive relationship for unsaturated soils.

The results of the study suggest that the MEBM is a simple approach that can be used with reasonable degree of confidence for predicting the vertical movements of unsaturated expansive soils considering all the environmental factors. The results of the study presented in this paper and three other case studies that were reported earlier in the literature (Vanapalli and Adem 2012, 2013, and Adem and Vanapalli 2013) are encouraging for extending the MEBM in engineering practice for rational design purposes of both the sub and superstructures constructed in or on expansive soils.

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