A simple technique to model temporary excavation support systems in unsaturated soils

Maha Saleh and Sai K. Vanapalli
Department of Civil Engineering – University of Ottawa, Ontario, Canada

ABSTRACT
Excavation support systems (ESS) are often located above the ground water table (GWT) where the soil is typically in an unsaturated state. The presence of capillary suction within the vadose zone contributes towards an increase in the soil shear strength and stiffness. However, current design procedures ignore the contribution of capillary suction and assume saturated soil conditions. This is because reliable prediction of the mechanical behavior of unsaturated soils is challenging. Meanwhile, extending saturated soil mechanics principles result in an erroneous design for ESS, especially in arid regions, where the GWT is typically deep. In this paper, a simple numerical technique is proposed to investigate the performance of cantilever diaphragm walls in unsaturated soils. The only information required in addition to the conventional saturated soil properties is the soil water characteristic curve. Numerical analysis is carried out with SIGMA/W to determine deformations and wall straining actions. The results of the study suggest that ignoring capillary suction results in a conservative design. In addition, estimates of deformations, forces and moments are erroneous. This study is of interest for practicing engineers as it provides a simple yet reliable approach for the rational design of ESS extending mechanics of unsaturated soils.

RÉSUMÉ
Les systèmes de support d'excavation sont souvent situés au-dessus de la nappe phréatique (GWT) où le sol est généralement dans un état non saturé. La présence d'une succion capillaire dans la zone vadose contribue à une augmentation de la résistance au cisaillement et de la rigidité du sol. Cependant, les procédures de conceptions actuelles ignorent la contribution de l'aspiration capillaire et supposent elles supposent que les des conditions de sol sont saturés. En effet, la prévision fiable du comportement mécanique des sols non saturés est difficile. Cependant, l'extension des principes de la mécanique des sols saturés entraîne une conception erronée des systèmes de support d'excavation, en particulier dans les régions arides, où le GWT est généralement profond. Dans cet article, une technique numérique simple est proposée pour étudier les performances des parois moulées en porte-à-faux dans les sols non saturés. La seule information requise en plus des propriétés conventionnelles du sol saturé est la courbe caractéristique de l'eau du sol. Une analyse numérique est réalisée avec SIGMA/W pour déterminer les déformations et les actions de déformation des parois. Les résultats de l'étude suggèrent que l'ignorance de la succion capillaire entraîne une conception conservatrice. Les estimations des déformations, des forces et des moments sont erronées. Cette étude est intéressante pour les ingénieurs en exercice car elle fournit une approche simple mais fiable pour la conception rationnelle de systèmes de support d'excavation étendant la mécanique des sols non saturés.

1 INTRODUCTION

Various commercial and residential developments, geotechnical infrastructure and transportation projects entailing underground construction widely use excavation support systems (ESS) during their execution. For example, cantilever or anchored sheet-pile/pile/diaphragm walls are often used as ESS in heavily populated urban regions, where space is limited. ESS are mainly intended for minimizing the disturbance of soil and for maintaining the stability of adjacent structures during excavation works. Standard design methods for ESS are based on limit equilibrium analysis which allows for the design of the wall and its components to satisfy overall stability (Bica and Clayton 1989). However, excavation works result in disturbance of the soil behind the wall leading to the settlement of adjacent buildings and roads. The wall may undergo lateral deformations and exceed its load carrying capacity. In addition to load capacity, surface soil settlement as well as lateral wall deformation are important factors that need to be considered in the rational design of ESS. The magnitude of lateral earth pressure acting on the wall is influenced by the wall movement. The overall stability of the system may be checked to achieve a reasonable accuracy using limit equilibrium methods; however, it is difficult to predict the soil settlement and deformations. This may be attributed to the influence of many factors including soil type, excavation depth, and system rigidity. Estimation of soil settlement and wall deformation requires a clear understanding of the soil-structure interaction. The limit equilibrium analysis is not capable to take all these parameters into account. For this reason, several guidelines have been developed to aid in the design of ESS (FHWA 1984, Rutherford et al. 2005, BSI 2007). These tools are useful for estimating the safe embedment depth of walls to support a desired excavation height in different soils. The suitable wall section can also be determined from readily available design charts to resist the resulting internal wall stresses. The maximum vertical surface settlement and the horizontal wall deformation which are to be expected due to a known excavation height are estimated from the case study results having similar soil conditions. In other words, the current state of practice for designing ESS relies to a large extent on empiricism, since the surface settlement and wall deformations are predicted from observations of case histories (Peck 1969, Goldberg et al. 1976, O'Rourke 1981). Due to these reasons, current design procedures have many limitations. To alleviate these limitations, finite element methods (FEM) have been recommended and used by several researchers for investigating the performance of ESS and predicting the resulting deformations (Lambe 1970, Clough and Tsui 1974, Clough and Mana 1977, Simpson 1992, Day 1999, Han et al. 2017). FEMs provide a reliable solution even for complex soil stratifications (multi-layered soil system) and geometries (surcharge) and most importantly, it facilitates sensitivity analysis. The design of ESS extending FEMs are conventionally based following the principles of saturated soil mechanics. The key parameters which are used in the design are the effective shear strength (c'& ϕ') and stiffness properties (E) of the soil as determined under saturated conditions using conventional experimental testing (i.e. triaxial tests, direct shear tests). As discussed earlier, in many situations, GWT is relatively deep and the retained soil behind the wall is in an unsaturated state. Within the unsaturated zone, the presence of capillary suction stresses ($u_a - u_w$) contributes towards an increase in the shear strength and stiffness of the soil. This has been confirmed from many experimental studies in the literature (Jennings and Burland 1962, Fredlund et al. 1978, Oh and Vanapalli 2011), as well as field tests (Russell et al. 2010, Yang and Russell 2015, Miller et al. 2018). These studies suggest that neglecting the influence of capillary suction in the design of ESS is erroneous. The rational design of ESS requires extending the principles of unsaturated soil mechanics in which the contribution of capillary suction to the mechanical properties of the soil is properly assessed. Such an approach provides a sustainable design, and in some scenarios, it likely contributes to economic benefits.

The variation in moisture content associated with environmental conditions (i.e. infiltration and evapo-transpiration) significantly contributes to variations in capillary suction. For this reason, information on the critical suction (i.e. lowest suction) profile is required in the design of ESS, considering the climatic conditions prevailing during the service life of the system. Also, the design life of ESS is usually short (one to two years) as these systems that act as temporary supports are no longer needed following the completion of construction of the underground structures. This serves as an additional motivation for considering capillary suction in the design of *temporary excavation support systems*.

In this paper, a simple numerical modeling technique is implemented to analyze ESS in unsaturated soils, extending the finite element analysis (FEA). The technique only requires the soil water characteristic curve (SWCC) in addition to the conventional saturated soil properties. The commercially available software SIGMA/W is used to investigate the performance of a 0.4m thick cantilever diaphragm wall having a length of 16m, during a 6m deep staged excavation, considering five different ground water table (GWT) depths below ground surface (0, 2, 4, 6, and 20m). The soil deformation, surface settlement, and the wall deformation and straining actions (i.e. bending moment and shear force) for the different GWT depths are compared extending conventional approach based on saturated soil mechanics and the rational approach extending the mechanics of unsaturated soils. The study summarized in this paper demonstrates that ignoring the contribution of capillary suction may result in a false assumption of potential instability of the system. This results in a deeper embedment depth or an additional lateral support will be required, which has significant cost implications on the project. In addition, estimations of deformations, forces and moments using conventional approach for unsaturated soils are likely to be erroneous.

2 BACKGROUND

2.1 Previous Studies on Earth Retaining Systems in Unsaturated Soils

A number of analytical frameworks were suggested by several scholars for the analysis of earth retaining structures in unsaturated soils (Pufahl et al. 1983, Hamid and Tawfik 2006, Tavakkoli and Vanapalli 2011, Li and Yang 2019). In these studies, the limit equilibrium analysis was extended to unsaturated soils to estimate the resulting active and passive earth pressures acting on retaining walls as affected by capillary suction. The modified Mohr-Coulomb failure criterion suggested by Fredlund et al. (1978) for unsaturated shear strength was used in the analysis. Basically, suction was considered as an apparent cohesion and added to the saturated soil strength. For a specific suction profile, the net lateral earth pressure along the wall depth could be reasonably estimated. These methods mainly focused on providing analytical procedures for quantifying the influence of suction on lateral earth pressure, while disregarding any soil-structure interaction. In other words, the influence of deformations on the resulting earth pressure was ignored. Moreover, these approaches did not address the impact of excavation works on neighbouring structures (i.e. surface settlement).

A limited number of experimental and field studies have been conducted recently to examine the performance of cantilever sheet piles (i.e. collapse load and deformation) in unsaturated soils. Borden et al. (2016) conducted a long-term field monitoring for a cantilever sheet pile wall in residual soils under different climatic conditions, including seasonal rainfall events. It was observed that the reduction in capillary suction due to rainfall resulted in an increase in deformations and a reduction in the overall safety factor of the wall. In addition, the rainfall regime did not result in a complete loss of capillary suction. This indicates the suitability of relying on the contribution of capillary suction to soil strength provided that a *critical suction profile* is used in the analysis. Shwan (2018) conducted three small-scale physical models for a cantilever pile wall in sand under dry, saturated, and one unsaturated condition. The experimental study focused only on the measurement of the wall displacements. Other parameters such as surface settlement, lateral earth pressure, and wall straining actions were not monitored during testing. The model consisted of a 0.7m x 0.15m x 0.4m reinforced glass chamber. Three different wall heights (0.22m, 0.24m, and 0.26m) and excavation depths (0.06m, 0.08m, and 0.1m) were tested. For unsaturated conditions, the water level was stabilized at excavation depth, which corresponded to a capillary suction value of about 2.6 kPa and a degree of saturation equal to 93%. Numerical analysis was also carried out to explore the mechanism of failure and the collapse load. The results of the physical model showed that the wall displacement under dry conditions was the largest and that capillary suction contributed to an 87% and 70% reduction in wall displacement as compared to dry and saturated conditions respectively. From the numerical analysis, a wider failure mechanism was observed for unsaturated conditions and the collapse load increased by 5.5 times as compared to the saturated condition. This study reveals that even within the low capillary suction range (i.e. < 3 kPa), the performance of cantilever walls can be significantly enhanced. Assuming saturated soil conditions for this case will result in an overestimation of wall deformation and an underestimation of the collapse load that can be safely carried by the cantilever wall.

2.2 Unsaturated Soil Property Functions

The shear strength (τ) and stiffness (E) of unsaturated soils are the two key parameters required for conducting FEA for ESS in unsaturated soils. τ will mainly govern the magnitude of the lateral earth pressure and the resulting stresses on the wall as well as overall stability of the system. This will be the controlling factor in the determination of the safe embedment depth. On the other hand, E will mainly influence the soil deformation. Experimental studies have shown that τ and E of unsaturated soils are highly influenced by the capillary suction (Jennings and Burland 1962). In a soil deposit, the capillary suction profile is not necessarily constant in the unsaturated zone. Therefore, the soil properties within the deposit will vary with respect to the capillary suction profile. Typically, the negative pore water pressure profile (which is equivalent to the capillary suction stress) above the water table is non-linear. The value of the negative pore water pressure will generally increase moving upward away from GWT. However, this profile is subjected to seasonal fluctuations. The magnitude of the pore water pressure is significantly affected by the changes in moisture content $(\omega\%)$ close to the natural ground level due to the influence of environmental factors; namely. rainfall and evapotranspiration.

The soil water characteristic curve (SWCC), which is the relationship between $\omega\%$ and capillary suction $(u_a - u_w)$, can be used as a tool to interpret the mechanical behavior of unsaturated soils. SWCC is dependent on the soil type, stress history, soil texture, soil mineralogy among other factors (Fredlund and Xing 1994, Vanapalli et al. 1999). Two variables, air entry value (AEV) and residual suction $(u_a - u_w)_r$ are important for predicting the behavior of unsaturated soil using SWCC. AEV is the suction value at which air begins to enter into the soil pores. This marks the onset of soil desaturation. Beyond this point, the rate of desaturation accelerates (i.e. moisture content begins to decrease rapidly). The residual suction, on the other hand, is the suction value beyond which the rate of desaturation diminishes significantly and the water phase becomes discontinuous (Vanapalli et al. 1996). The remainder of water takes on the form of adsorbed water and it cannot be reduced any further, despite high suction values. The shear strength and stiffness of the soil will increase linearly with the increase in suction up to AEV. Beyond AEV, the contribution of suction to shear strength and stiffness starts decreasing, resulting in a non-linear variation of the mechanical properties (i.e. shear strength and stiffness).

Fredlund et al. (1978) extended the Mohr-Coulomb failure criterion to unsaturated soils. A theoretical framework was developed for estimating the variation of shear strength with respect to suction:

$$\tau_{unsat} = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \qquad [1]$$

where σ = nomal stress, c' = effective cohesion, ϕ' = effective angle of internal friction, u_a = pore air pressure, u_w = pore water pressure, ϕ^b = angle of internal friction with respect to suction.

The shear strength of unsaturated soils can be measured using suction-controlled experimental testing. However, these procedures are time-consuming and expensive. Therefore, alternative prediction methods were developed which provide a reliable estimate of shear strength using saturated soil properties and SWCC. Among these methods, the model developed by Vanapalli et al. (1996) is generally simple to apply. It alleviates the need for determining ϕ^b and it requires a limited number of parameters:

$$\tau_{unsat} = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)\tan\phi' \qquad [2]$$

where θ is the volumetric water content, θ_s is the saturated volumetric water content, and θ_r is the residual volumetric moisture content. Vanapalli et al. (1996) also proposed a second model:

$$\tau_{unsat} = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)S^{\kappa}\tan\phi' \qquad [3]$$

where S is the degree of saturation and κ is a fitting parameter which is related to plasticity index. For cohesionless soils, $\kappa = 1.0$.

Several studies are available in the literature to investigate the variation of the modulus of elasticity with respect to suction in unsaturated soils. In this paper, the modulus of elasticity of unsaturated soils (E_{unsat}) was estimated from SWCC using the model proposed by Oh and Vanapalli (2009):

$$E_{unsat} = E_{sat}\left[1 + \alpha \frac{(u_a - u_w)}{\left(P_a/_{101.3}\right)}\left(S^{\beta}\right)\right] \qquad [4]$$

where E_{sat} is the modulus of elasticity under saturated conditions. α is a fitting parameter related to plasticity index. β is a fitting parameter related to soil type and it can be taken equal to 1.0 and 2.0 for cohesionless and cohesive soils respectively.

3 NUMERICAL MODELING

A typical silt is chosen to be used in the parametric study. The selected soil properties are summarized in Table 1. The SWCC information for "silt" is selected from the database of the commercial software GeoStudio 2020 (Figure 1). The database facilitates in selecting a reasonable SWCC in the absence of information for a measured SWCC. However, the SWCC can be measured in the laboratory using the axis translation technique or it can be predicted from the grain size distribution and plasticity index information (Vanapalli and Catana 2005, Houston et al. 2006, Chin et al. 2010)

The two-dimensional plane-strain FEA is carried out using the commercial software SIGMA/W (which is one of the modules available in Geostudio 2020). The left and right boundaries are restrained in the horizontal direction while the bottom boundary is restrained in both the vertical and horizontal direction. The modified effective stress approach is adopted in the analysis, and the soil is modeled using the elastic-perfectly plastic Mohr-Coulomb soil model. This model is common for analyzing geotechnical engineering problems. However, in case of problems involving excavation activities, it may result in an over estimation of basal heave at the bottom of the excavation since it uses the same elastic modulus for loading and unloading conditions. The hyperbolic soil model (or hardening soil model) may provide a better estimate of the heave but it requires the determination of the unload/reload elastic modulus. Since the main objective of this study is to compare the behavior of the wall under different wetting conditions rather than obtain an accurate estimate for deformations, the Mohr-Coulomb model is considered satisfactory for fulfilling this objective. The wall is modeled as a beam element and the input parameters required include the elastic modulus for concrete as well as the cross-sectional area and the moment of inertia for the rectangular section (thickness = 0.4m). The selected mesh type consists of quadrilateral and triangular elements with a size of 0.4m. A typical cantilever diaphragm wall with a length of 16m and a thickness of 0.4m is considered in the present study. The model size adopted in the analysis has a height of 20m and a width of 60m. Staged excavation down to 6m depth is done in three stages, each having a depth of 2m. A total of five different GWT depths are studied (0, 2, 4, 6, and 20m below ground surface). The model is shown in Figure 2.

The design suction profile needs to account for environmental factors such as evapotranspiration and rainfall. This requires a seepage analysis using local climatic data as well as the soil hydraulic properties (coefficient of permeability k). Typically, the insitu capillary suction profile is non-linear. However, in the present study, seepage analysis is not undertaken, and a hydrostatic pore water pressure profile is assumed above and below the water table, for simplicity reasons. The negative pore water pressure, which is the height above the water table multiplied by the unit weight of water, corresponds to the capillary suction. Below the water table, the pore water pressure is positive, and is equal to the unit weight of water multiplied by the depth below GWT.

Table 1. Engineering properties of the typical silt.

Soil properties	Silt
Unit weight, γ (kN/m^3)	20
Drained cohesion, c' (kPa)	5
Drained friction angle, ϕ' (^{0})	20
Saturated Modulus of elasticity, E_{sat} (kPa)	5000
Saturated coefficient of permeability, k_{sat} (m/s)	1e-6
Saturated volumetric water content, θ_{sat}	0.5

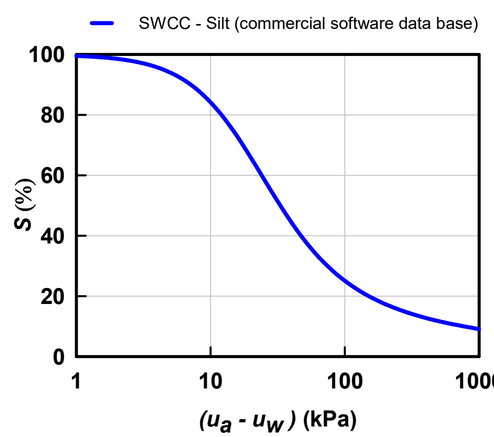

Figure 1. SWCC for the silt used in the present study (from commercial software data base).

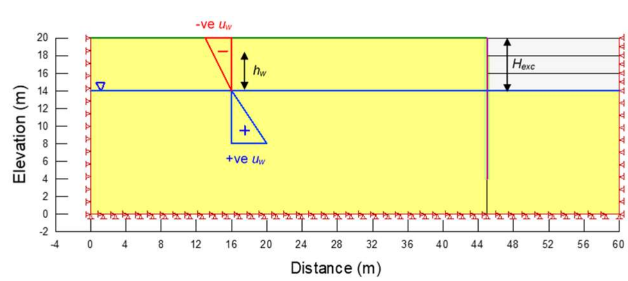

Figure 2. FEA model for the cantilever diaphragm wall.

It should be noted that the change in stress state due to excavation results in changes in the initial capillary suction profile. These changes can be accounted for by considering a coupled stress analysis type in which the equilibrium (displacement) and continuity (flow) equations are solved simultaneously (GEO-SLOPE 2017). In this case, the hydraulic boundary condition can be implemented as a total head at the left model boundary. The pore water pressure across the soil due to excavation is then automatically calculated by the software. The total cohesion is also automatically calculated using the defined SWCC and the calculated capillary suction profile. The commercial software adopts equation [2] in determining the corresponding apparent cohesion. As for the modulus of elasticity, the automatic calculation option is not available in the software used. Therefore, the unsaturated modulus of elasticity is calculated manually using equation [3] for the corresponding initial suction profile. It can be defined in the model as a variable Y vs E function (elevation versus modulus of elasticity). The variation of the modulus of elasticity with respect to depth for each GWT depth is shown in Figure 3.

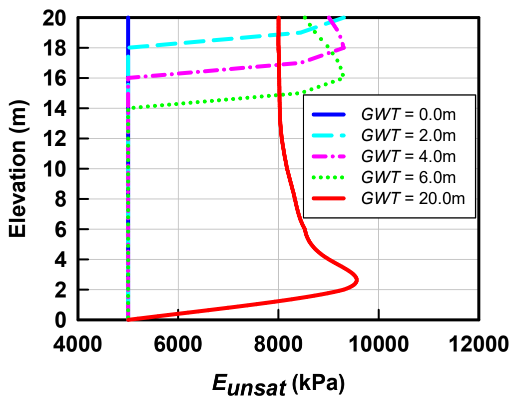

Figure 3. Variation of E_{unsat} with respect to elevation due to the contribution of suction for different GWT scenarios.

4 ANALYSIS OF RESULTS

The key indicators for the performance of ESS are the surface settlement of the soil behind the wall, the wall deformation and the straining actions (moments and shear). The magnitude of these variables is used to check the serviceability and overall stability of the selected system. If the estimated variables exceed the capacity of the system under consideration, then a second iteration is done considering a more rigid system. For example, if the soil or wall deformation are found to be relatively high, then internal struts or tie back anchors are deemed necessary in order to control the deformations. The embedment depth of the wall may also be increased to ensure overall stability and to reduce wall deformation. These relevant variables were determined for the different GWT depth scenarios (0, 2, 4, 6, and 20m below ground surface), following the staged excavation down to 6m below initial ground surface (i.e. Elev 14m).

Based on the analysis, the contribution of capillary suction to shear strength and stiffness in case of the deeper GWT depths resulted in a significant reduction in the overall deformations and the magnitude of bending moments and shear force acting on the wall and enhanced the performance of the system significantly. Figure 4 shows the variation in soil deformation for the different GWT depths.

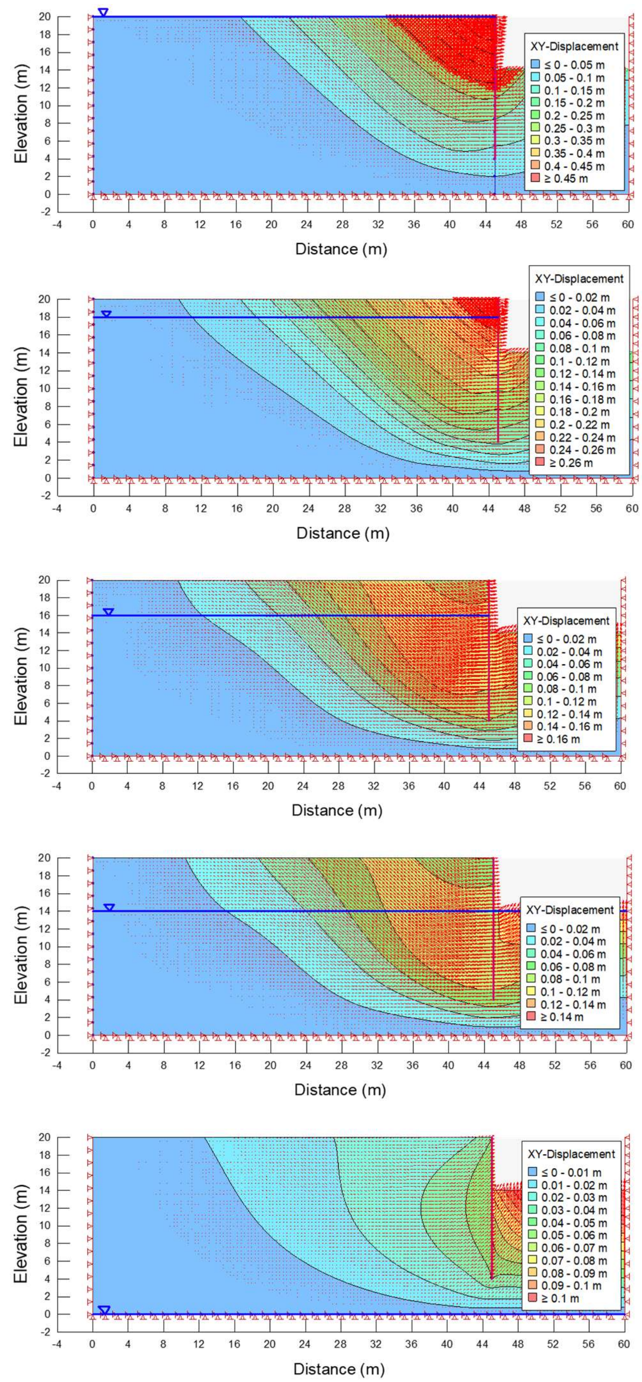

Figure 4. Soil deformation after excavation for the different *GWT* scenarios.

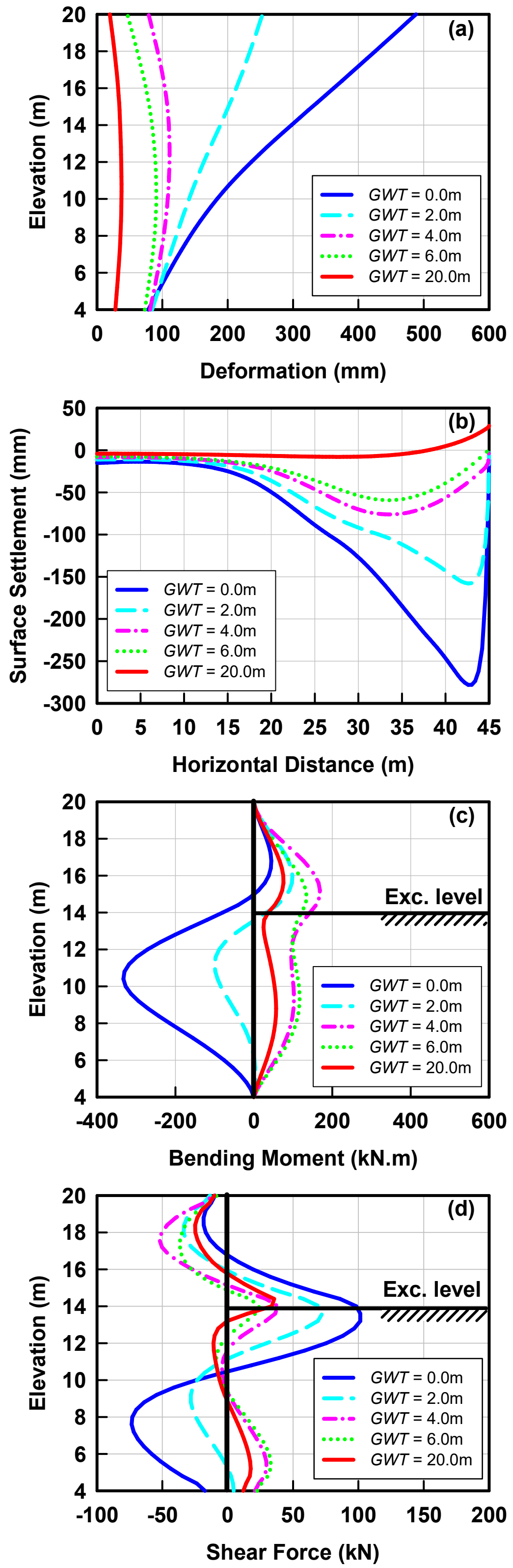

Figure 5. Variation of (a) wall deformation, (b) surface settlement, (c) bending moment, and (d) shear force along the wall for different *GWT* depth.

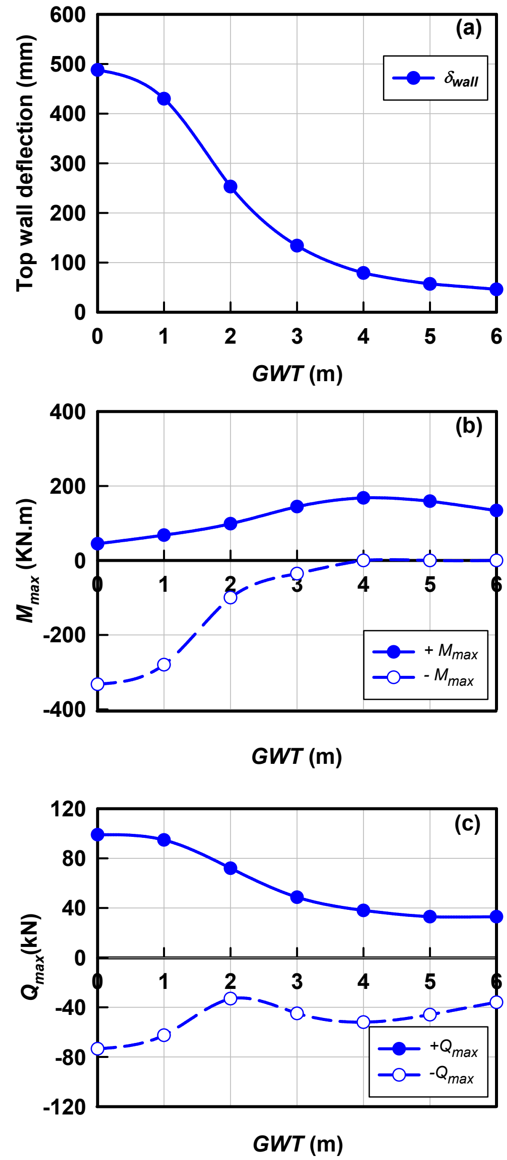

Figure 6. Variation of (a) top wall deflection, (b) maximum +ve and -ve bending moment, and (c) maximum +ve and -ve shear force with respect to GWT depth.

As expected, the maximum soil deformation profile was observed for the case of saturated condition (i.e. GWT=0m). Then, the soil deformation was found to decrease gradually as the GWT depth increased.

The deformation of the wall along its depth was plotted for the different GWT scenarios, as shown in Figure 5(a). For saturated conditions, the excavation resulted in significantly higher wall deformation than for the deepest GWT case. The resulting wall deformation suggests the need for additional lateral support (bracing or tie-back anchors) to limit wall deformations induced by the 6m deep excavation. Moreover, the shape of deflection for the wall was observed to vary significantly. For the saturated soil conditions, the maximum wall deformation was found to be close to the excavation level. On the other hand, the maximum wall deflection was observed to be located just above the midspan of the wall for the unsaturated conditions. The influence of the excavation on the adjacent land was checked by examining surface settlement which is shown in Figure 5(b). It is evident that the surface settlement profile changes significantly with the lowering of GWT. The capillary suction contributes towards a significant decrease in surface settlement behind the wall as well as the location of maximum settlement. The surface settlement was found to be 10 times higher for saturated conditions as compared to the deepest GWT (i.e. GWT at 20.0m).

The structural capacity of the wall was checked by estimating the bending moment and shear force resulting from the lateral earth pressure. Figure 5(c) shows the variation in the bending moment (BM) diagram along the wall following the 6m deep excavation. The results indicate that the shape of BM diagram can vary significantly for the considered GWT scenarios. The negative moment generally decreased with the increase in GWT depth below ground surface whereas the positive moment did not follow a uniform trend. Irrespective of the variation in the form of the bending moment diagram, the highest BM was observed for the saturated conditions whilst the lowest BM was observed for the deepest GWT depth. The same conclusion applies to the shear force diagram (Figure 5 (d)).

Figure 6 (a, b, & c) show the variation of top wall deflection, maximum positive and negative bending moments, and maximum positive and negative shear force with respect to GWT, respectively. As shown in the figure, these variables vary non-linearly with respect to GWT. In general, the influence of capillary suction was observed to be significant at low values corresponding to shallow GWT. On the other hand, the contribution of capillary suction towards the overall performance of the cantilever wall appears to reduce for deeper GWT levels despite the increase in the suction profile.

5 SUMMARY AND CONCLUSIONS

The study summarized in this paper highlights some limitations of the conventional methods that are used in the design of excavation support systems (ESS) in unsaturated soils. Monitoring results of executed ESS suggest that these methods result in an overestimation of the associated deformations and straining actions. The presence of capillary suction stresses in unsaturated soils, among other factors, may attribute to this inconsistency. Therefore, the focus of this paper is directed towards investigating the influence of capillary suction on the performance of ESS.

A simple numerical technique, extending FEA, is used to investigate the performance of cantilever diaphragm walls in a typical silt considering different GWT depths to simulate both saturated and different unsaturated soil conditions. For simplicity, a hydrostatic negative pore water pressure distribution is assumed in the present study. However, a non-linear capillary suction profile obtained from field measurements or seepage analysis can also be accommodated. The soil is modeled as an elastic-perfectly plastic material with pore water pressure changes, extending the effective stress approach. The unsaturated soil shear strength and stiffness are predicted using the saturated soil properties and the SWCC.

The results of the analysis show that the overall performance of the diaphragm wall improves significantly for the deeper GWT levels, due to the role of capillary suction. In general, both the soil deformation as well as the wall deflection and stresses under unsaturated conditions were found to be lower in comparison to saturated soil conditions. However, the resulting changes in the distribution of straining actions (i.e. bending moment and shear force) along the wall length clearly indicate that there are other factors which also influence the performance of the wall (i.e. soil-structure interaction). Moreover, a threshold GWT depth is identified below which the change in the wall performance becomes negligible. The relatively high capillary suction values (corresponding to a deep GWT) which develop near ground surface do not always contribute towards enhancing the mechanical behavior of the soil. Therefore, a clear understanding of the SWCC is necessary to explain the behavior of ESS in unsaturated soils.

In summary, it is concluded from the present study, that ignoring the contribution of capillary suction in the design of cantilever diaphragm walls results in a conservative design. The conventional method over-estimates ground movement and wall deflection. The false assumption of potential instability or excessive deformations suggests the need for increasing the rigidity of the system in order to minimize the surface settlement and wall movement to acceptable limits. As a result, additional lateral support (i.e. internal bracings or tie-back anchors) or a deeper embedment depth are required. Moreover, the overestimated straining actions entail a larger wall section to satisfy the structural stability of the system. Therefore, understanding the role of capillary suction and considering its contribution to the mechanical properties (i.e. shear strength and stiffness) of the soil contribute not only in the reliable design but also in project savings. Most ESS have a short design life span (typically, 1 to 2 years) and they only serve as temporary structures. The role of ESS ends once the underground structure is complete. This means that the initial suction profile is not likely to vary significantly throughout the lifetime of the excavation support system. In other words, the uncertainties in predicting the critical (design) suction profile are minimal for such scenarios.

The implemented numerical technique is promising for use in practice to analyze complex ESS with multilayers of bracings and tie-back anchors. Experimental verification of the suggested approach is in progress to investigate and validate the contribution of suction and to propose a reliable framework for designing ESS in unsaturated soils.

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