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ABSTRACT

Lateral swelling pressure (LSP) develops in silty or clayey soil when the volume expansion of soil is constrained in the horizontal direction. Determination of LSP is important in designing geotechnical structures in expansive soils. Existing methods for derivation of LSP requires several empirical parameters, which are hard to obtain. Furthermore, the majority of the existing models determine LSP assuming the soil is fully saturated which may lead to an over conservative design. Considering the aforementioned limitations, this paper presents an analytical solution for determination of LSP in unsaturated soils. The proposed method attributes the soil expansion to changes in suction stress during infiltration and uses the effective stress-strain relationship to quantify LSP. The proposed model only needs a limited number of soil properties such as the soil water retention curve (SWRC) and Poisson's ratio along with initial and final soil water contents. The method is compared against an alternative solution and is then used in a set of parametric study to evaluate LSP for four soils. Results suggest that the proposed model can reasonably predict LSP in expansive soils.

INTRODUCTION

Expansive soils can deform in both lateral and vertical directions due to changes in water content. This class of fine-grained soil is frequently found in arid and semi-arid regions of the world (Nelson and Miller, 1992) where the environment is suitable for formation of clayey soils. Under low water contents, expansive soils would expand when the applied pressure reduces and/or the moisture content increases. On the other hand, expansive soils with high water content would shrink when their water content decreases. During infiltration, if the soil is constrained in the horizontal direction (e.g., by a retaining wall), the lateral swelling pressure (LSP) will develop in the soil and impose an extra stress on the structure or infrastructure in addition to the lateral earth pressure (LEP) caused by soil unit weight and/or surcharge. The excess earth pressure can lead to various problems in geo-structures built within or in adjacent to expansive soils (Chen, 1988). Previous studies have shown that LSP have caused damages to piles and other structures buried in expansive soils (Kassiff and Zeitlen, 1962). For instance, Kurzeme and Richards (1974) monitored soil suction and earth pressure behind a 7.5 m deep basement wall over a long time period in a clayey soil and reported LEP increases at the bottom of the wall equal to 1.3-4 times the overburden. They attributed this observation to the accumulation of water in the initial gap between the wall and the clay, followed by the local swelling of the clay. An increase in LEP affects the stability and safety of geotechnical structures and may finally cause them to fail (Kassiff and Zeitlen, 1962; Ng et al., 2003; Liu and Vanapalli, 2017). The Annual cost of damages associated with expansive soils in the United States has been reported as much as $13 billion (Puppala and Cerato, 2009). Thus, the influence of LSP must be considered in the design of geotechnical structures in expansive soils.

Vertical swelling pressure arises when a structure (e.g., foundation) restricts the ground heave and LSP develops when the lateral volume expansion of expansive soil is restricted by a geo-structure such as basement walls. Fig. 1 schematically demonstrates the development of LSP behind a retaining structure. The unsaturated backfill soil can be divided into active and steady zones (Lu and Likos, 2004). In the steady zone, which is located in high depths of the unsaturated layer, the suction profile is independent of time. In contrast, in the active zone, which includes shallow and near-surface soils, the suction profile is affected by seasonal environmental changes such as infiltration and thus, varies with time. When there is a prolonged precipitation, pore-water pressure in the active zone may experience significant reductions (e.g., Leshchinsky et al., 2015), which can mobilize LSP in expansive soils.

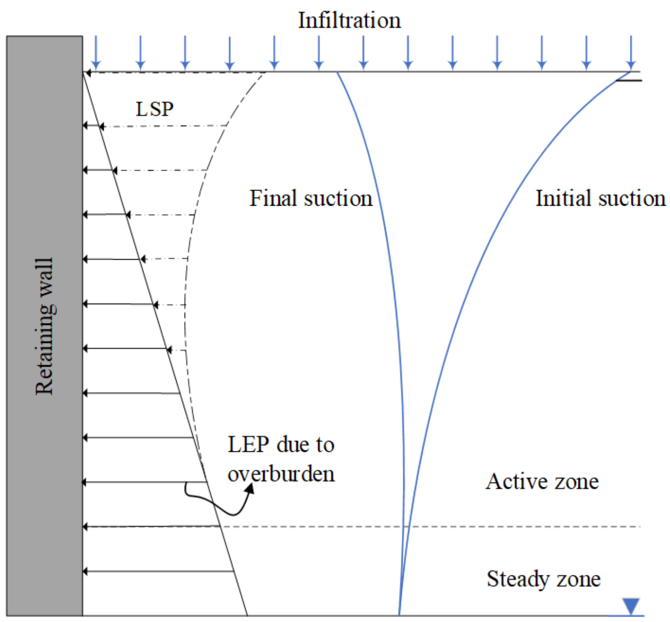

Figure 1. Distribution of lateral earth pressure behind a retaining wall.

Several studies have been devoted to problems conjugated to LSP of expansive soils over the past few decades (e.g., Kassiff and Zeitlen, 1962; Komornik and Zeitlen, 1965; Chen, 1988; Puppala and Cerato, 2009; Nelson et al., 2015). These studies include laboratory and in-situ experimental testing, numerical methods, and analytical solutions. Several investigators have introduced modifications to the traditional odometer and hydraulic triaxial apparatus in order to measure the swelling pressure in both vertical and lateral directions (e.g., Komornik and Zeitlen, 1965; Fourie, 1989; Windal and Shahrour, 2002; Abbas et al., 2015; Monroy et al., 2015). Large-scale tests and in-situ investigations were also used to determine LEP considering the effect of swelling pressure (Robertson and Wagener, 1975; Ofer, 1980; Katti et al., 1983; Mohamed et al., 2014). However, field tests demand a long time period for data collection. Previous studies have also proposed semi-empirical and empirical equations for predicting LSP (e.g., Skempton, 1961; Jiang and Qin, 1991; Hong, 2008; Nelson et al., 2015). For instance, Liu and Vanapalli (2017) proposed an analytical solution to determine LSP using vertical swelling pressure, which they referred to as the minimum vertical stress required to prevent the vertical swelling during soaking. Liu and Vanapalli (2019a) extended the latter work to account for partially saturated conditions. Ikizler et al. (2014) developed a model using artificial neural network and adaptive neuro-fuzzy inference systems to predict LSP in expansive soils.

The majority of existing methods for calculating LSP are either relatively complex or require several empirical parameters, which are not always easy to obtain. In addition, almost all of these models can only determine LSP when the soil is fully saturated after the infiltration, which is not always the case in real field conditions. To address the aforementioned limitations, the current study presents a closed-from model for determination of LSP in expansive backfills. The model is capable of predicting LSP in the unsaturated state and only needs a limited number of soil properties such as Poisson's ratio and the soil water retention curve (SWRC).

PROPOSED METHOD

In this study, we develop an analytical solution for the LSP by employing a suction stress-based representation of effective stress (Lu and Likos, 2004, 2006). We conceptualize that LSP is primarily controlled by infiltration-induced changes in suction stress of a laterally constrained unsaturated soil. Implementing suction stress into the proposed model allows to independently account for the effect of matric suction and effective degree of saturation, characterized using the SWRC. Finally, effective stress-strain relationships in the unsaturated soil layer is used to develop an analytical solution for determination of LEP accounting for the contributions of both overburden and swelling pressure.

Effective Stress for Unsaturated Soils

In this study, the generalized effective stress (σ') expression for unsaturated soils given by Bishop (1959) is used as:

$$\sigma' = \sigma - u_a + \chi\psi \tag{1}$$

where σ is total stress, u_a is the pore-air pressure, χ is Bishop's effective stress parameter, and ψ is matric suction. The term $-\chi\psi$ in Bishop's effective stress expression is referred to as suction stress, σ^s (e.g., Lu and Likos, 2006; Lu et al. 2010). Using this definition, Bishop's effective stress expression that unifies both saturated and unsaturated conditions can be rewritten as (Lu and Likos, 2006):

$$\sigma' = \sigma - u_a - \sigma^s \tag{2}$$

For unsaturated soils, the suction stress can be defined as (Lu et al., 2010):

$$\sigma^s = -\psi \times S_e \tag{3}$$

where S_e is the effective degree of saturation and can be obtained using the van Genuchten (1980) SWRC model as follow:

$$S_e = \frac{S - S_r}{1 - S_r} = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{1}{1 + (\alpha\psi)^n}\right)^{(1 - \frac{1}{n})} \tag{4}$$

where S is the degree of saturation, S_r is the residual saturation, θ is volumetric water content, θ_s is saturated water content, θ_r is residual water content, α is a fitting parameter inversely related to the air-entry suction (1/kPa), and n is the pore-size distribution fitting parameter.

At-Rest Earth Pressure in Unsaturated Soils

Hooke's law is a linear stress-strain constitutive equation, which is commonly used to establish a relationship between vertical and horizontal stress components. Hooke's law can be extended to unsaturated soils by incorporating the suction stress-based effective stress representation as follows (Lu and Likos, 2004; Shahrokhabadi et al., 2019):

$$\varepsilon_x = \frac{\sigma_x - u_a}{E} - \frac{\mu}{E}\left(\sigma_y + \sigma_z - 2u_a\right) - \frac{1-2\mu}{E}\sigma^s \tag{5a}$$

$$\varepsilon_y = \frac{\sigma_y - u_a}{E} - \frac{\mu}{E}\left(\sigma_x + \sigma_z - 2u_a\right) - \frac{1-2\mu}{E}\sigma^s \tag{5b}$$

$$\varepsilon_z = \frac{\sigma_z - u_a}{E} - \frac{\mu}{E}\left(\sigma_x + \sigma_y - 2u_a\right) - \frac{1-2\mu}{E}\sigma^s \tag{5c}$$

where ε_x, ε_y, and ε_z are elastic strains in the x, y, and z directions, respectively; σ_x, σ_y, and σ_z are elastic total stresses in the horizontal and vertical directions (Fig. 2); and E and μ represent Young's modulus and Poisson's ratio.

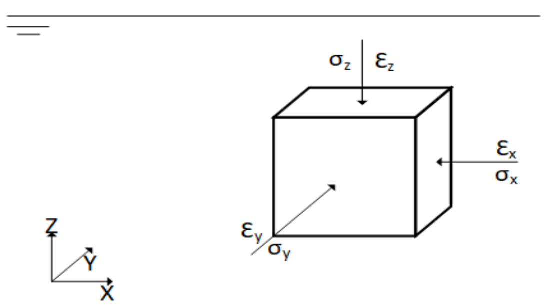

Figure 2. Vertical and horizontal stresses and strains in unsaturated soil element.

For a homogenous unsaturated soil layer in a half-space domain, the following two assumptions can be used (Lu and Likos, 2004):

1. The horizontal stresses are equal ($\sigma_x = \sigma_y = \sigma_h$).

2. The horizontal strains are negligible ($\varepsilon_x = \varepsilon_y = \varepsilon_h = 0$).

Imposing these assumptions reduces Eq. (5) to:

$$\varepsilon_v = \frac{\sigma_v - u_a}{E} - \frac{2\mu}{E}(\sigma_h - u_a) - \frac{1-2\mu}{E}\sigma^s \tag{6a}$$

$$\varepsilon_h = \frac{\sigma_h - u_a}{E} - \frac{\mu}{E}(\sigma_v + \sigma_h - 2u_a) - \frac{1-2\mu}{E}\sigma^s \tag{6b}$$

where ε_v and σ_v are the strain and stress in the vertical direction, and ε_h and σ_h are the strain and stress in horizontal direction.

Stress State Change in Analytical Elements upon Swelling

In order to determine LSP, a representative soil element behind the retaining wall is considered (Fig. 3). As it can be seen, two different horizontal pressure components are applied to the element:

1. LSP: horizontal pressure due to the infiltration-induced change in suction stress (i.e., $\Delta\sigma^s = \sigma^s_{final} - \sigma^s_{initial}$).
2. σ_l: horizontal pressure due to the overburden pressure (σ_v).

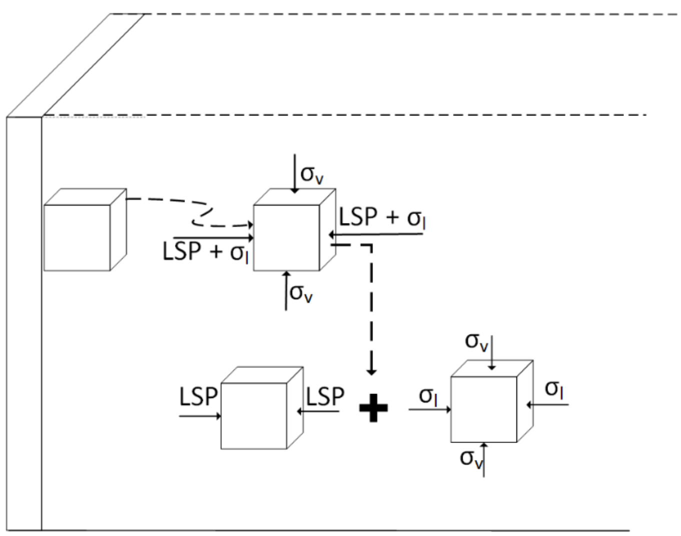

Figure 3. Analytical element of expansive soil behind a retaining structure.

The above two conditions imply that $LEP = LSP + \sigma_l$. It is also assumed the soil can move vertically, meaning that the vertical stress is only due to overburden and no vertical stress is added by swelling. Assuming the pore-air pressure is equal to atmospheric pressure with a relative value of zero and using Eqs. 6(a) and 6(b), the horizontal effective stress-strain relation in the soil element can be described as follows:

- For the soil element subjected to the swelling pressure only:

$$\varepsilon_h = 0 = \frac{LSP}{E} - \frac{\mu}{E}LSP - \frac{1-2\mu}{E}(\sigma^s_{final} - \sigma^s_{initial}) \tag{7}$$

- For the soil element subjected to the overburden pressure only:

$$\varepsilon_h = 0 = \frac{-\sigma_l}{E} + \frac{\mu}{E}(\sigma_v + \sigma_l) \tag{8}$$

Solving Eqs. (7) and (8), the LEP components due to the overburden and swelling can be obtained as follows:

$$LSP = \left(\frac{1-2\mu}{1-\mu}\right)(\sigma^s_{final} - \sigma^s_{initial}) \tag{9a}$$

$$\sigma_l = \left(\frac{\mu}{1-\mu}\right)\sigma_v \tag{9b}$$

By applying the superposition method, a general LEP estimation model can be proposed that includes both the effect of swelling and surcharge as:

$$LEP = LSP + \sigma_l = \left(\frac{1-2\mu}{1-\mu}\right)(\sigma^S_{final} - \sigma^s_{initial}) + \frac{\mu}{1-\mu}\sigma_v \tag{10}$$

COMPARISON WITH AN ALTERNATIVE MODEL

The results of the proposed formulation are compared against those attained from an alternative method proposed by Liu and Vanapalli (2019b). They developed a three-step computer program for evaluation of single pile behavior in unsaturated expansive soil under infiltration. Liu and Vanapalli (2019b) considered the effect of LSP in LEP, which was later used to determine the pile's shaft friction. Their proposed model showed good agreement with the results obtained from field and laboratory tests. Fig. 4 shows the problem geometry and matric suction profiles during infiltration.

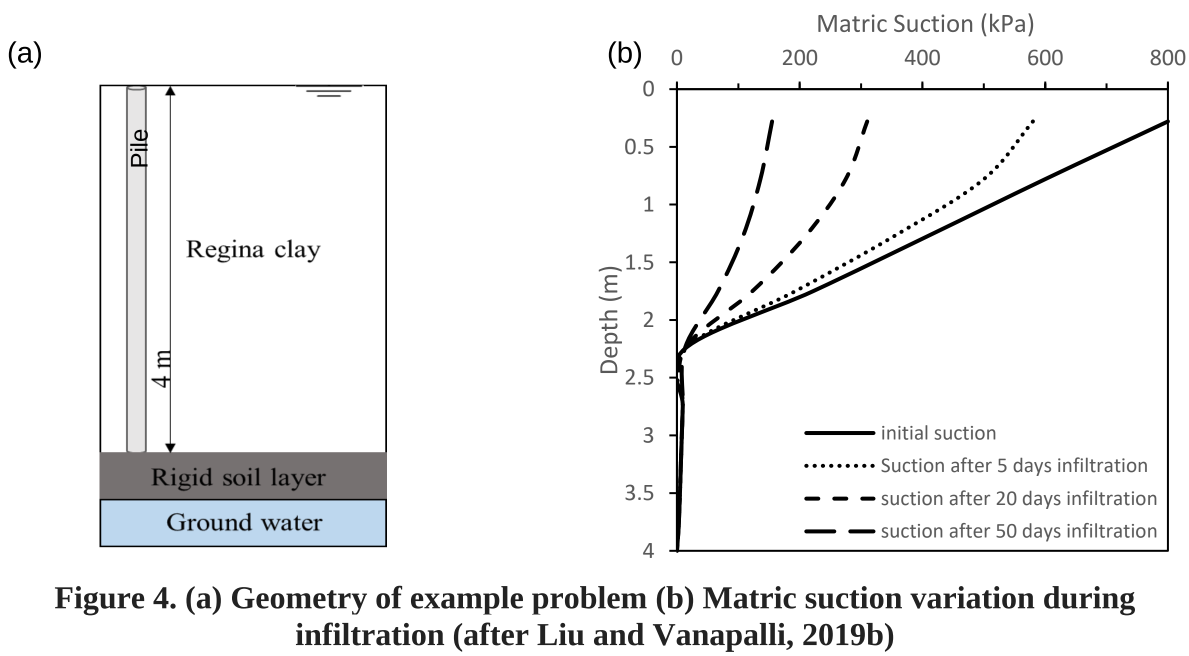

Figure 4. (a) Geometry of example problem (b) Matric suction variation during infiltration (after Liu and Vanapalli, 2019b)

As shown in Fig. 5, there is a good agreement between the proposed method and analytical solution developed by Liu and Vanapalli (2019b) whom used the net normal stress and matric suction as independent stress state variables. In depth more than 2 m below the ground surface, no significant difference exists between the initial and final suction, thus LEP in this zone is solely because of the overburden pressure.

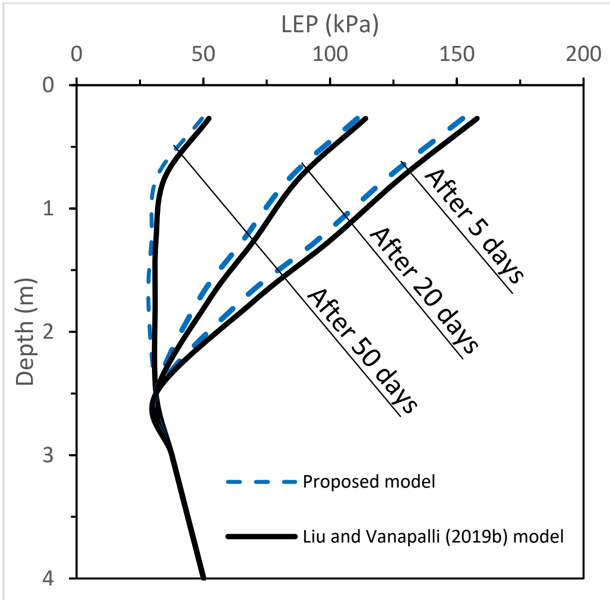

Figure 5. Comparison of LEP by the proposed model and Liu and Vanapalli (2019b).

PARAMETRIC STUDY

When the water table is deep, it is reasonable to assume that suction profile is uniform in the backfill soil. The constant suction profile with depth has also been reported in large model experimental tests for evaluation of LSP (e.g., Komornik, 1962; Joshi and Katti, 1980). In this section and in order to investigate LSP in different soils, the initial and final suctions are assumed to be uniform along the depth and equal to 500 and 20 kPa, respectively. Soil properties are summarized in Table 1.

Table 2 presents the calculated LSP for each soil using Eq. 9a. As the initial and final suction profiles are constant with depth, LSP is uniform at each depth behind the retaining structure. From Table 2, it is evident that there is a direct relation between suction stress and swelling pressure, and higher suction stress difference between the initial and final conditions results in higher values of LSP. Table 2 shows that LSP in silty soil is much lower than that in clayey soil. This can be attributed to the value of α, which heavily controls the shape of the soil's suction profiles and the magnitude of suction stress profiles. Large α values represent relatively large pore sizes and smaller air entry head, resulting in small degrees of saturation. Physically, the degree of saturation defines the portion of matric suction that contributes to suction stress. Clayey soils can convert up to 100% of matric suction into suction stress (Lu and Likos, 2004).

Table 1. Hydrological and mechanical properties of different expansive soils

Soil	$\alpha\ (\frac{1}{kPa})$	n	PI	Expansive soil classification	USCS classification	μ	Reference
Georgia Kaolinite	0.004	2.20	18	-	CH	0.25	Lu et al. (2014)
Missouri Clay	0.022	1.57	19	Expansive	CL	0.25	Lu and Dong (2017)
Bonny Silt	0.091	1.53	4	Low-Expansive	ML	0.25	Lu and Dong (2017)
Regina Clay	0.002	1.30	44	Expansive	-	0.4	Vu and Fredlund (2004)

Table 2 also shows clayey soils with higher plasticity index values tend to develop larger LSP under infiltration. Finally, the effect of Poisson's ratio on the magnitude of LSP should be noted. Unlike LEP due to overburden, higher values of Poisson's ratio may lead to lower contribution of suction stress in LSP. As an example, despite the significant difference in the initial and final suction stressws in Regina clay (406 kPa), the soil develops LSP almost equal to Georgia clay, which has a difference of 175 kPa between its initial and final suction stresses.

Table 2. Lateral swelling pressure for different expansive soils

Parameter	Georgia Kaolinite	Missouri Clay	Bonny Silt	Regina Clay
Suction Stress difference (kPa)	175.54	108.10	53.04	406.07
Swelling Pressure (kPa)	117.03	72.06	35.36	135.35

CONCLUSION

Development of LSP in expansive soils (i.e., silty and clayey soils) under water infiltration can significantly lower the factor of safety of retaining walls, basement walls, or buried geo-structures. In this study, development of LEP considering the effect of LSP against retaining earthen structures is evaluated. In the study, LSP is defined as a function of infiltration-induced changes in suction stress for a laterally constrained unsaturated soil. An analytical solution for LSP is derived by employing a suction stress-based representation of effective stress, the soil water retention curve, and extended Hook's law for unsaturated soils. The proposed analytical solution is used to study the effect of soil properties on LSP. Results showed that LSP is affected by soil water characteristic curve parameters, where soils with higher values of air entry tends to develop greater LSP under identical suction change. It was found that the Poisson's ratio plays an important role in the magnitude of LSP, where higher values of Poisson's ratio may not necessarily result in higher values of LSP. In general, the proposed method can be used to evaluate LSP in expansive soils under infiltration. The model only requires the basic properties of expansive soil such as the SWRC and Poisson's ratio in order to calculate LSP. Unlike the majority of proposed models, it is also able to measure the swelling pressure in unsaturated conditions after infiltration.

REFERENCES

Abbas, M. F., Elkady, T. Y., and Al-Shamrani, M. A. (2015). Evaluation of strain and stress states of a compacted highly expansive soil using a thin-walled odometer. *Eng. Geol.*, 193, 132–145.

Bishop, A.W. (1959). The principle of effective stress. *Tek. Ukeblad*, 106 (39), 859–863.

Chen, F. H. (1988). Foundations on expansive soils, Elsevier, New York. (2012). Prediction of swelling potential and pressure in compacted clay. *Arabian J. Sci. Eng.*, 37(6), 1535–1546.

Fourie, A. B. (1989). Laboratory evaluating of lateral swelling pressure. *J. Geotech. Eng.*, 10.1061/(ASCE)0733-9410(1989)115:10(1481), 1481–1486.

Hong, G. T. (2008). Earth pressures and deformations in civil infrastructure in expansive soils. *Ph.D. dissertation, Texas A&M Univ.*, College Station, TX

Ikizler S B, Vekli M, Dogan E, Aytekin M, Kocabas F. (2014) Prediction of swelling pressures of expansive soils using soft computing methods *J. Neural Computing and Applications*, 2012, 24(2): 1−13.

Jiang, Z.X., Qin, X.L. (1991). A new method for calculating lateral swell pressure in expansive soil. *In: Proceedings of 7th International Conference on Expansive Soils*, Dallas, Texas, USA, 1, 233–238.

Joshi, R.P. and Katti, R.K. (1980). Lateral Pressure Development under Surcharges. *Proceedings of the 4th International Conference on Expansive Soils*, Denver, CO, 227-241.

Kassiff, G. and Zeitlen, J.G. (1962). Behaviors of pipes buried in expansive clays. *In: Proc. ASCE J. Soil Mech. Found. Eng.*, SM 2, No. 3103.

Katti, R. K., Bhangle, E. S., and Moza, K. K. (1983). Lateral earth pressure of expansive soil with and without a cohesive non-swelling soil layer—Applications to earth pressures of cross drainage structures of canals and key walls of dams (studies of Ko condition). *Technical Rep. No. 32*, Central Board of Irrigation and Power, New Delhi, India.

Komornik, A. (1962). The Effect of Swelling Properties of Unsaturated Clay on Pile Foundations. D.Sc. *Thesis, Israel Institute of Technology*.

Komornik, A. and Zeitlen, J.G. (1965). An apparatus for measuring lateral soil swelling pressure in the laboratory. *In: Proceedings of 6th conference on soil mechanics and foundation engineering*, Canada, 1, 278–281.

Kurzeme, M. and Richards, B. G. (1974). Earth Pressure Observations on a Retaining Wall in Expansive Clay. Gouger Street Mail Exchange, Adelaide, Division of Applied Geomechanics *Technical Report 17*. Australia: CSIRO.

Leshchinsky, B., Vahedifard, F., Koo, H-B., and Kim, S-H., (2015). Yumokjeong Landslide: An Investigation of Progressive Failure of a Hillslope using the Finite Element Method. *Landslides*, 12(5), 997-1005.

Liu, Y., Vanapalli, S. K. (2017). Influence of lateral swelling pressure on the geotechnical infrastructure in expansive soils. *J. Geotech. Geoenviron*. Eng. 143 (6).

Liu, Y. and Vanapalli, S. K. (2019a). Load displacement analysis of a single pile in an unsaturated expansive soil. *J. Computers and Geotechnics*, 106, 83-98, ISSN 0266-352X.

Liu, Y., & Vanapalli, S. K. (2019b). Prediction of lateral swelling pressure behind retaining structure with expansive soil as backfill. *Soils and Foundations*, *59*(1), 176-195.

Lu, N., and Likos, W. J. (2004). Unsaturated soil mechanics, Wiley, New York.

Lu, N., and Likos, W. J. (2006). Suction stress characteristic curve for unsaturated soils. *J. Geotech. Geoenviron. Eng.*, 10.1061/(ASCE) 1090-0241(2006)132:2(131), 131–142.

Lu, N., Godt, J. W., and Wu, D. T. (2010). A closed-form equation for effective stress in unsaturated soil. *Water Resour. Res.*, 46(5), W05515.

Mohamed, O. Z., Taha, Y. K., and El-Aziz, E. M. (2014). Field study of the distribution of lateral swelling pressure of expansive soil on the retaining structure. *J. Eng. Sci*., 42(2), 289–302.

Monroy R, Zdravkovic L, and Ridley AM (2015) Mechanical behavior of unsaturated expansive clay under K0 conditions. *Eng Geol* 197:112–131.

Nelson, J. D., and Miller, D. J. (1992) Expansive soils. Willy, New York.

Nelson, J. D., Chao, K. C., Overton, D. D., and Nelson, E. J. (2015). *Foundation engineering for expansive soils*, Wiley, Hoboken, NJ.

Ng, C.W.W., Zhan, L.T., Bao, C.G., Fredlund, D.G., and Gong, B.W. (2003). Performance of an unsaturated expansive soil slope subjected to artificial rainfall infiltration. *Geotechnique* 53 (2), 143–157.

Ofer, Z. (1980). Instruments for laboratory and in-situ measurements of LSP of expansive clays. Proc., *4th Int. Conf. on Expansive Soils, ASCE and International Society for Soil Mechanics and Foundation Engineering*, Reston, VA, 45–53.

Puppala, A. J., and Cerato, A. (2009). Heave distress problems in chemically-treated sulfate-laden materials. *Geo-Strata*, 10(2), 28–32.

Robertson, A. M. G. and, Wangener, F.V. M. (1975). Lateral swelling pressure in active clay. *In: Proceedings of 6th Conference for Africa on Soil Mechanics and Foundation Engineering*, Durban, South Africa, 107–114.

Shahrokhabadi, S, Vahedifard, F., Ghazanfari, E., and, Foroutan, M. (2019). Earth pressure profiles in unsaturated soils under transient flow. *Engineering Geology*, DOI: 10.1016/j.enggeo.2019.105218.

Skempton, A.W. (1961). Horizontal stresses in an over consolidated Eocene clay. *In: Proceeding of 5th International Conference on Soil Mechanics and Foundation Engineering*, Paris, 1, 351–357.

van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J*., 44(5), 892–898.

Windal, T., and Shahrour, I. (2002). Study of the swelling behavior of a compacted soil using flexible odometer. *Mech. Res. Commun*., 29(5), 375–382.