Estimation of uplift shaft friction for a single pile in expansive soil using the mechanics of unsaturated soils

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Pile foundations that are installed in unsaturated expansive soils are subjected to uplift forces along the pile shaft due to the swelling of the expansive soils upon infiltration. This leads to the redistribution of the pile axial force and possible upward movement of the pile body. For this reason, it is necessary to take into account of uplift shaft friction by determining or estimating the uplift shaft friction along the shaft in the rational design of piles in expansive soils considering the influence of lateral swelling pressure. In this paper, the conventional β method for calculating pile lateral friction is modified to estimate the uplift shaft friction for a single pile in expansive soils upon infiltration considering the influence of lateral swelling pressure and matric suction. The proposed method is successfully validated using the experimental data by Fan (2007).

RÉSUMÉ
Les fondations sur pieux installées dans les sols gonflants non saturés sont soumises à des forces de soulèvement tout le long du fût des pieux dues au gonflement des sols lors de l'infiltration d'eau. Cela conduit à la redistribution de la force axiale du pieu et à son possible déplacement vers le haut. Pour cette raison, il est nécessaire de tenir compte du soulèvement frictionnel du fût du pieu en déterminant ou en estimant ce dernier dans la conception rationnelle des pieux dans les sols gonflants, tout en prenant en compte l'influence de la pression de gonflement latérale. Dans cet article, la méthode conventionnelle β pour le calcul du frottement latéral du pieu est modifiée pour permettre d'estimer le soulèvement frictionnel d'un pieu isolé en tenant compte de l'influence de la pression de gonflement et de la succion matricielle. La méthode proposée est validée avec succès en utilisant les données expérimentales produites par Fan (2007).

1 INTRODUCTION

The swelling and shrinkage characteristics associated with the fluctuations in water content of unsaturated expansive soils has a significant influence on the engineering properties such as the coefficient of permeability, shear strength properties and volume change. For this reason, it is a challenge to design infrastructure such as the pile foundations within expansive soils. Government agencies, contractors, owners, consultants and insurance companies are forced to invest significant financial resources to reduce infrastructure losses due to expansive soils. These losses are associated with the claims, repairing, redesigning and retrofitting or in some scenarios abandoning of infrastructure constructed with or within expansive soils.

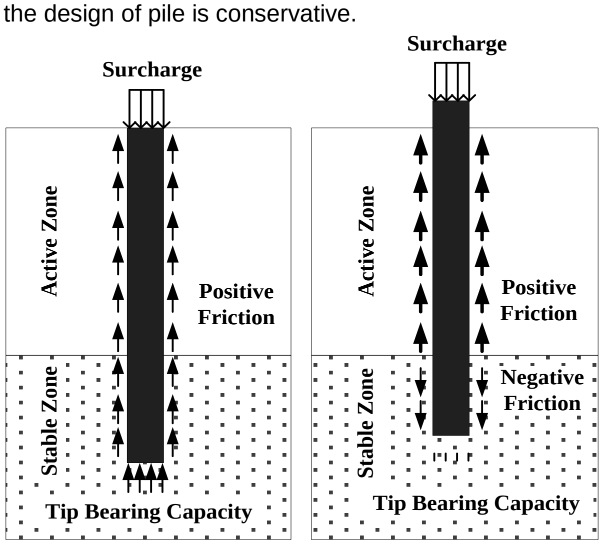
Pile foundations carry significantly large loads from the superstructure safely without stability or deformation problems in a variety of soils. These types of foundations are also used in expansive soils by introducing minor modifications in their design and construction procedures. However, the influence of matric suction and swelling pressure on the load carrying capacity and deformation behavior of pile foundations placed in unsaturated expansive soils are neglected extending the assumption that the design is conservative using saturated soil mechanics. The uplift friction that generates along the pile length upon infiltration as a result of displacement between the pile and adjacent soil (i.e. soil swells and moves upward relative to the pile) is not given due consideration that it deserves in the design of piles. The shaft friction that generates along the pile length contributes to the redistribution of axial force in the pile. In some scenarios, the uplift force applied on the pile may exceed the withholding force and the pile may be pulled up and likely cause serious damages to the superstructure. The present understanding of the comprehensive behavior of piles in expansive soils is rather limited (Nelson et al. 2015). For this reason, it is recommended or encouraged to conduct in-situ pile tests to obtain data for use in the reliable design and construction of pile foundations in expansive soils (MOHURD 2013). Some investigators have been depending on numerical analyses to better understand the complexities associated with the uplift movement of piles in expansive soils (Justo et al. 1984; Chen 1988; Nelson et al. 2015). However, numerical analyses techniques require complex constitutive relationships that need many soil parameters for modeling and in-situ pile testing is expensive and time-consuming. For engineering practice applications, a quick, simple and acceptable method to estimate the uplift shaft friction is required. Such a method will assist geotechnical engineers to provide rational design procedures for pile foundations in unsaturated expansive soils both with respect to understanding the stability and deformation behavior. In this paper, to achieve this objective, the modified β method by Vanapalli and Taylan (2012) which is based on conventional β

method proposed by Chandler (1968) and Burland (1973) is extended to predict the uplift shaft friction along a single pile in expansive soil generating upon infiltration using the mechanics of unsaturated soils.

2 BACKGROUND

2.1 Shaft Friction Generation along the Length of Single Pile in Expansive Soil

Figure 1 shows the comparison of shaft friction distribution along the length of pile in expansive soil before and after infiltration. In an unsaturated expansive soil, prior to infiltration, positive friction is distributed along the entire length of the pile and carries the load together with some contribution from the tip or end [as shown in Figure 1 (a)]. However, as water infiltrates into the active zone, expansive soil swells [as shown in Figure 1 (b)]. Positive friction increases in the active zone and negative friction arises in the stable zone (i.e. soils at a depth that do not influenced by water infiltration). Pile tends to move upward together as expansive soils typically swell upon infiltration. Theoretically, the net contribution that arises from negative shaft friction, tip or end bearing capacity and surcharge combine to prevent the pile from being pulled up in an expansive soil. However, tip or end bearing capacity contribution towards the load carrying capacity decreases significantly when there is an upward movement in pile and hence can be neglected such that the design of pile is conservative.



(a) Before infiltration (b) After infiltration

Figure 1. Distribution of shaft friction along a pile before and after infiltration

The contribution of shaft friction can be attributed to three factors: the normal stress applied on the interface, the roughness of the pile-soil interface and the differential displacement between pile and soil.

Both the peak shear strength and residual shear strength generating from the pile-soil interface can be assumed to follow the Mohr-Coulomb failure criterion (Fan 2007; Hamid and Miller 2009). The influence of normal stress and interface properties can be described using two terms, internal friction angle and cohesion of the pile-soil interface using Eq. (1) given below.

$$f = \sigma \tan \delta + c \qquad [1]$$

where σ = normal stress acting on the interface; δ = internal friction angle; c = cohesion

As for normal stress acting on the pile shaft, apart from the soil self-weight and surcharge, there is a significant contribution arising from lateral swelling pressure which should be given due consideration. Figure 2 illustrates the lateral pressure distribution along a single pile in expansive soil upon infiltration.

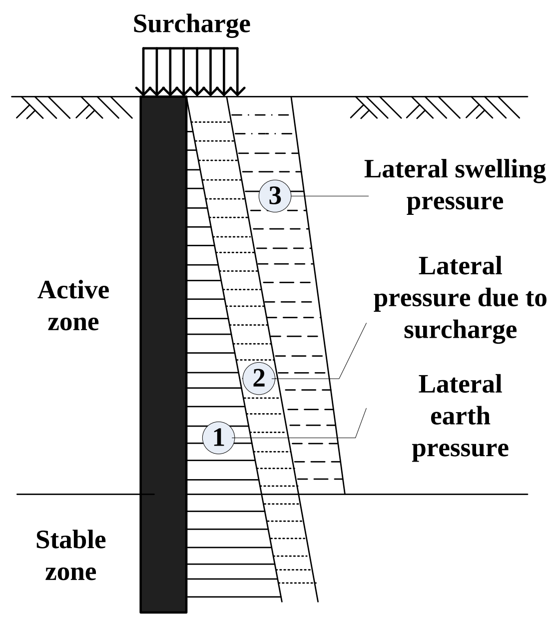


Figure 2. Distribution of lateral pressure along a pile upon infiltration (modified after Ertekin 1991)

Other than normal stress and pile-soil interface properties, magnitude of shaft friction is also affected by relative displacement between the pile and soil. Figure 3 describes typical shear strength and displacement behavior which also includes shear softening (for example, Yin et al. 1994; Fan 2007). The deformation behavior along the interface during shearing can be simplified and explained using Figure 4. The shear of the interface can be divided into two phases: (i) elastic deformation that occurs between pile and soil; (ii) failure or plastic deformation that occurs between a thin layer of soil adjacent to the pile (i.e. shearing zone) and remainder of the soil. The peak shear strength (τ_p) typically occurs at the point where elastic deformation stage ceases and its value equals the sum of the friction and cohesion between pile and soil. However, at failure or plastic stage, slip occurs between the pile and soil. A thin soil layer (i.e. shearing zone) typically adheres to the pile. Shear strength at this stage generates only from friction between shearing zone and the remainder of the soil. The contribution from cohesion between pile and soil suddenly disappears or reduces rapidly and leads to a collapse of shear strength to a residual value (τ_r) as shown in Figure 3.

In engineering practice, peak shear strength values are suggested to be used in the design as it gives to a larger uplift shaft friction and contribute to a conservative design.

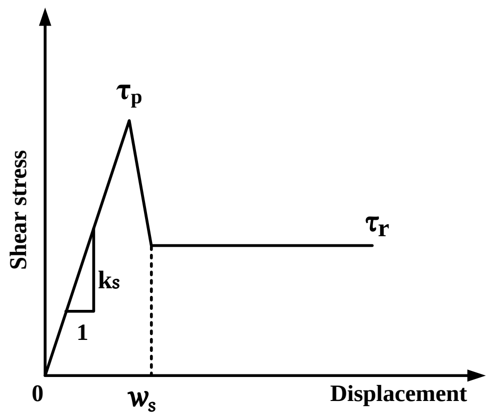


Figure 3. Relationship between the shear stress and pile-soil displacement

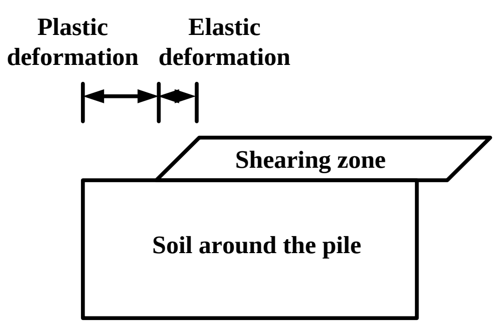


Figure 4. Deformation of the pile-soil interface

2.2 Suggestions for Modifications to the β Method

The β method originally proposed by Chandler (1968) and later expanded by Burland (1973) is a simple and efficient method to estimate the skin friction, Q_f of piles in soils with low percentage of fines such as silty sands and normally consolidated clays. In Eq. (2), β is introduced as the Burland-Bjerrum coefficient to describe the relationship between the vertical effective stress and skin friction.

$$Q_f = f_s A_s = \beta \sigma_z' \pi d L \qquad [2]$$

where $\beta = K_0 \tan\delta'$, K_0 = mean lateral earth coefficient at rest, δ' = effective friction angle of pile-soil interface, d = the diameter of the pile, L= the length of the pile.

Vanapalli and Taylan (2012) modified the conventional β method [i.e. Eq. (2)] to predict the shaft friction of single piles in unsaturated fine-grained soils for drained loading conditions taking into account the contribution of matric suction.

$$f_{(us)} = c_a' + \beta(\sigma_z') + (u_a - u_w) S^{\kappa} \tan\delta' \qquad [3]$$

where δ' = internal friction angle of pile-soil interface for saturated condition, c_a' = adhesion component of cohesion for saturated condition, S = degree of saturation, κ = fitting parameter for shear strength (Vanapalli et al. 1996; Vanapalli and Fredlund 2000; Garven and Vanapalli 2006).

In this equation, the total shaft friction is composed of two parts: the first part represents the contribution from net normal stress and cohesion (i.e. $f_{us(nns)} = c_a' + \beta(\sigma_z')$) and the second part arises from the contribution of matric suction (i.e. $f_{(us)ms} = (u_a - u_w) S^{\kappa} \tan\delta'$). This equation can be extended for piles in expansive soil, if there is no swelling associated with water infiltration.

However, with an increase in water content, expansive soils show strong swelling potential in all directions. In most cases, soil swells freely in the vertical direction as crawl space is typically provided between structure and pile foundation to accommodate this expected movement (as shown in Figure 5). However, if volume expansion is restricted in horizontal direction, swelling potential would arise in the form of lateral swelling pressure. This lateral swelling pressure acts on the pile shaft together with the parts form soil self-weight and surcharge.

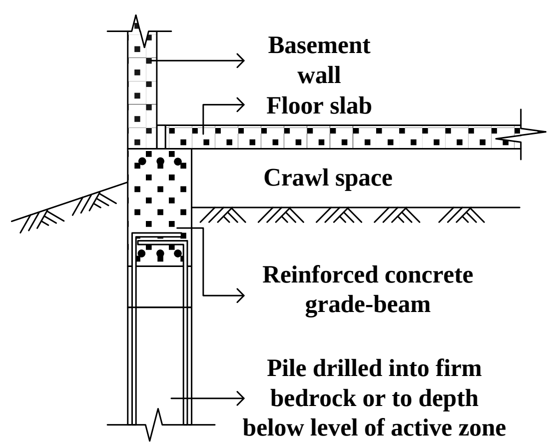


Figure 5. Pile and grade beam system typically used in expansive soil to accommodate vertical swelling

As the modified β method proposed by Vanapalli and Taylan (2012) has already considered the influence of matric suction, in this study focus is directed towards including the influence of lateral swelling pressure.

Swelling pressure is a key factor that is used in the literature to describe the swelling behavior of expansive soils. Significant research has been undertaken during the last several decades to better understand the swell pressure (Jennings and Knight 1957; Navy 1971; Fredlund et al. 1980; Basma et al. 1995; Alonso et al. 1999; Lytton et al. 2004; Azam et al. 2013; Briaud et al. 2013). However, main focus of the research studies of expansive soils with respect to swelling behavior were directed to understand the vertical swelling pressure. This value is generally considered to be the maximum pressure in the vertical direction that arises due to the infiltration process. Estimation of vertical swelling pressure methods can be summarized into three categories; namely, empirical methods, soil suction based methods and oedometer methods. Each category has provided reasonable estimation methods (Brackley 1973; Sridharan et al. 1986; Rao 2006; Vanapalli and Lu 2012; Çimen et al. 2012). However, compared with vertical swelling pressure methods, studies with respect to understanding lateral swelling pressure is limited and are mostly based on limited laboratory studies (Ertekin 1991). In this paper, a theoretical equation is derived for describing the relationship between the vertical swelling and lateral swelling pressure imposed on the pile shaft. This relationship can be included into the modified β method proposed by Vanapalli and Taylan (2012) to estimate the uplift friction generating along the pile during the infiltration process.

3 PROPOSED METHOD

3.1 Assumptions Used in the Proposed Method

Figure 6 provides a schematic highlighting a single pile in expansive soil along with a soil element surrounding the pile. This element represents a segment of a hollow cylinder as shown in the figure. Upon infiltration, the volume of this hollow cylindrical element tends to expand inward and outward simultaneously. The inward expansion is restricted by the pile; due to this reason, the restricted swelling potential translates into lateral swelling pressure and acts on the pile. It is likely that there will be some outward expansion that can develop and contribute to a significant reduction of the lateral swelling pressure acting on the pile shaft. The outward expansion is assumed to be restricted such so as to provide a more conservative estimation. Uplift shaft friction is likely to increase due to the contribution of lateral swelling pressure, when it also contribute a considerable part compared with the lateral swell pressure caused by soil weight or surcharge.

To derive this relationship an analytical element is considered from the hollow cylinder [Figure 6 (a)] as shown in Figure 6 (b). Since the research focus is targeted on a thin layer surrounding the pile for estimating uplift shaft friction, the difference among the side lengths of the analytical unit can be neglected. In order to simplify the calculation, the analytical unit can be assumed to be a cube element as shown in Figure 6 (c).

3.2 Proposed Theoretical Approach

A simple theoretical approach is proposed in this paper to estimate the uplift shaft friction along a pile in an unsaturated expansive soil that is swelling. The soil around the pile is assumed to be linear elastic, homogeneous and isotropic. The objective is to simulate a scenario of restricting the horizontal volume deformation in an element which initially swells with a decrease in matric suction and then gets compressed back to its initial condition due to the influence of a vertical stress. These two stages along with their respective stress and strain states are shown in Figure 7. Each of these stress and strain states is described below:

(i) Stage (a) shows how the element fully swells due to a reduction in matric suction while the horizontal volume deformation is restricted by horizontal confining stress σ_3. As a consequence, the vertical side lengths of the element increase from *c* to *b*.

(ii) Horizontal confining stress σ'_3 and vertical stress σ'_1 are applied to the element simultaneously as shown in Stage (b). The vertical side length reduces from *b* to *c* while the horizontal side length keeps constant.

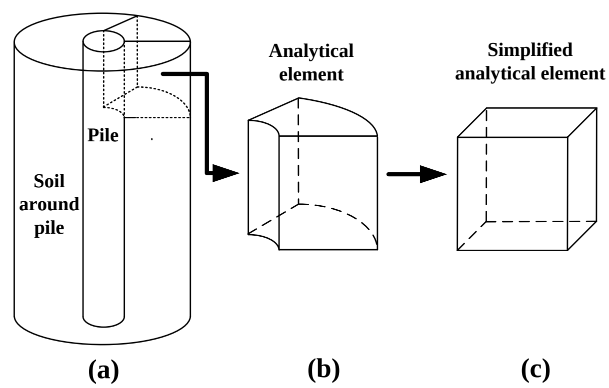


Figure 6. Schematic of the soil surrounding a pile along with an element that is used for analyzing soil stresses

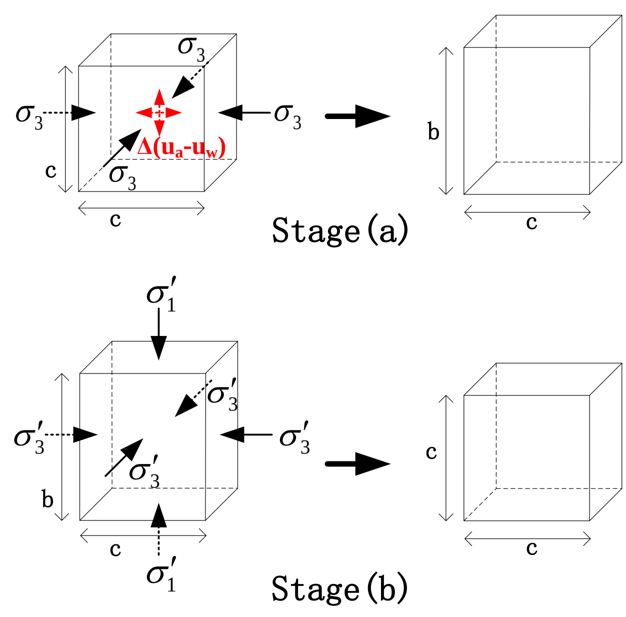


Figure 7. Stress and corresponding deformation for two different stages

Fredlund and Morgenstern (1976) provided constitutive relations [Eq. (4)] extending continuum mechanics theory for unsaturated soils in terms of two independent stress state variables, $(\sigma-u_a)$ and (u_a-u_w).

$$\begin{cases} \varepsilon_x = \dfrac{(\sigma_x-u_a)}{E} - \dfrac{\upsilon}{E}(\sigma_y+\sigma_z-2u_a) + \dfrac{\Delta(\sigma_x-u_a)}{H} \\ \varepsilon_y = \dfrac{(\sigma_y-u_a)}{E} - \dfrac{\upsilon}{E}(\sigma_x+\sigma_z-2u_a) + \dfrac{\Delta(\sigma_y-u_a)}{H} \\ \varepsilon_z = \dfrac{(\sigma_z-u_a)}{E} - \dfrac{\upsilon}{E}(\sigma_y+\sigma_x-2u_a) + \dfrac{\Delta(\sigma_z-u_a)}{H} \end{cases} \quad [4]$$

where E = modulus of elasticity, υ = Poisson ratio, H = suction modulus which can be roughly estimated through $H=\frac{E}{1-2\upsilon}$ (Wong et al. 1998; Zhang et al. 2012).

The above constitutive relationships can be used for estimating the stress-strain relationships for stage (a) and stage (b) shown in Figure 7. In stage (b), σ_1' corresponds to the vertical swelling pressure, P_s, since it prevents the possible vertical expansion of expansive soils. The value of P_s can be determined from laboratory tests or calculated using various semi-empirical or empirical equations (Vanapalli and Lu 2012, Çimen et al. 2012). Solving these equations, the relationship between vertical stress, σ_1', and the initial horizontal confining stress, σ_3, can be developed as shown in Eq. (5).

$$\sigma_3 = \frac{(1-\upsilon-2\upsilon^2)P_s}{\frac{P_s}{E}(1+\upsilon)(1-\upsilon-2\upsilon^2)+1-\upsilon^2} \quad [5]$$

Eq. (5) is suitable for estimating the lateral pressure in surface soil layer without the influence of surcharge. In addition, for this scenario, soil expansion is not restricted in the vertical direction but restricted lateral swelling potential translates into lateral swelling pressure. However, for soil layers at greater depths, the influence of surcharge (including the soil weight of upper soil layers or/and surcharge of upper structures), σ_s, should be taken into account. Corresponding stress and strain states [stage (c) and stage (d)] are shown in Figure 8.

A more general equation [Eq. (6)] is deduced by including the influence of horizontal confining stress into Eq. (5). For surface soil layer without surcharge, σ_s in Eq. (6), which represents the surcharge is equal to zero.

$$\sigma_3 = \frac{(1-\upsilon-2\upsilon^2)P_s}{\frac{P_s}{E}(1+\upsilon)(1-\upsilon-2\upsilon^2)+1-\upsilon^2} + \sigma_s \quad [6]$$

By substituting Eq. (6) into Eq. (3), the influence of lateral swelling pressure acting on pile shaft can be included into the modified β method to estimate the uplift shaft friction that develops along the pile [Eq. (7)].

$$f = c_a' + \tan\delta'\{K_0\gamma h + \frac{(1-\upsilon-2\upsilon^2)P_s}{\frac{P_s}{E}(1+\upsilon)(1-\upsilon-2\upsilon^2)+1-\upsilon^2} + \sigma_s + (u_a-u_w)S^{\kappa}\} \quad [7]$$

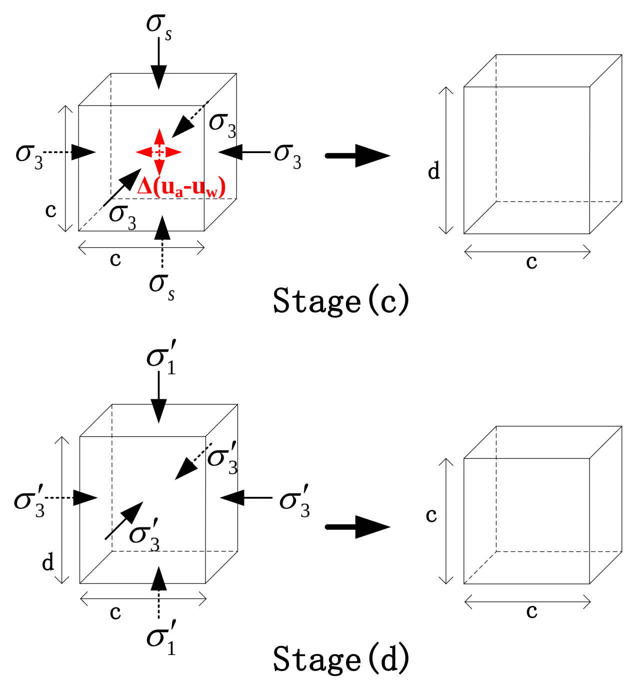


Figure 8. Influence of surcharge on horizontal confining stress

4 VERIFICATION OF THE PROPOSED METHOD

Experimental results of Fan (2007) performed on a single model pile in an expansive soil which is subjected to infiltration is used in this paper for verification of the proposed method.

The model pile and test tank are shown in Figure 9. The tank was 900 mm in height and 500 mm in diameter. Three layers of different soils were filled in the test tank with 100 mm gravel in the bottom, 160 mm medium sand in the middle and 580 mm expansive soil in the top. Expansive soil used in this experiment is a compacted expansive soil that was collected from Nanning, Guangxi province in China. The soil properties were summarized in Table 1. The expansive soil was compacted with a degree of compaction higher than 90%. The 650 mm long model pile was made of a PVC pipe with fly-ash inside. A sand layer was adhered to the surface to create a rough surface. The tip of the pile rests on the sand layer. Vertical and horizontal sand drains were distributed in the tank to facilitate the seepage of water.

Strain gauges were installed at different depths along length of the pile (as shown in Figure 9) so that the pile axial stresses can be back-calculated through the measured strains. An earth pressure cell was installed below the pile tip to measure the tip or end bearing capacity. Settlements of pile and soil were measured using dial gauges.

Table 1. Properties of expansive soil in the test tank

Property	Nanning soil
Liquid limit, w_L(%)	48.1
Plastic limit, w_P (%)	21.2
Plastic index, I_P	26.9
Maximum dry density (Mg/m^3)	1.89
Optimum water content (%)	15.8

The compacted expansive soil in the tank was irrigated such that the optimum water content (15.8%) achieves full saturation condition. The recorded heave of expansive soil was 41.2 mm and the upward movement of the pile was 3.59 mm.

Fan (2007) developed a finite element program to study the behavior of piles in expansive soil upon infiltration. In this program, a new constitutive model was developed by modifying Barcelona Basic Model extending elastic-plastic models (Alonso et al. 1990). The pile, sand and gravel were considered to be fully elastic. The parameters used in the simulation are given in Table 2. The experimental study results were used to validate the program. The simulated soil heave was 39.53 mm and the upward settlement of the pile was 5.71 mm.

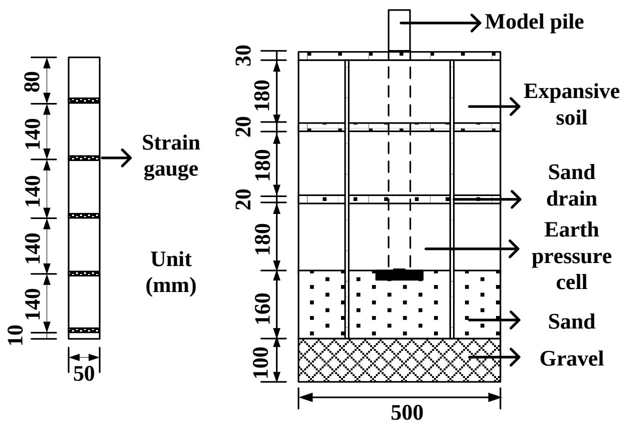


Figure 9. Model pile and test tank used in the experimental study (modified after Fan 2007)

The comparison between the measured and simulated pile axial stress distribution curves and shaft friction distribution curves are given in Figure 10 and Figure 11, respectively. The maximum axial stress is approximately at the midpoint of the pile. The reasons for this phenomenon are given as below: The heave of expansive soil in shallow soil layers is typically more in comparison in soil layers at greater depths. Compared with the upward movement of pile, within shallow soil layers, expansive soil moves upward relative to pile so positive friction generates in this zone. However, for soil layers at greater depth, expansive soil moves downward relative to pile so negative friction generates in this zone (as shown in Figure 11).

Since the simulated results of Fan (2007) show good comparison with the experimental results (Figure 10), the same soil parameters were used to check the validity of the method proposed in this paper.

Table 2. Parameters used in simulation

Property	Nanning soil
Elastic modulus, E (MPa)	5.94
Poisson ratio, υ	0.3
Friction angle of the interface, δ' (°)	35.4
Cohesion of the interface, c' (kPa)	46.7

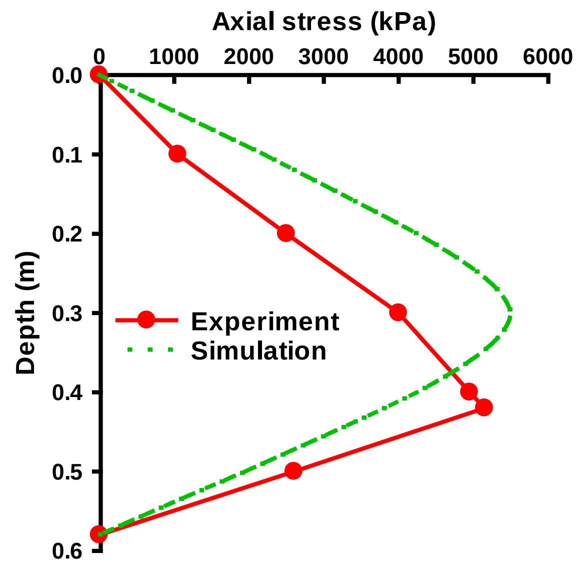


Figure 10. Comparison between pile axial stress distribution curves

Besides the soil parameters listed in Table 2, vertical swelling pressure information is also required for calculation of frictional shaft resistance using Eq. (7). Fan (2007) conducted a series of constant volume swell tests to study the vertical swelling pressure using soil specimens compacted at different initial water contents. The compacted soil specimens used in these tests had similar properties with the soil filled in the test tank (as shown in Table 3). Vertical swelling pressure of 400 kPa was measured when the soil specimen was saturated from initial water content of 15.8% in the soil tank, which is close to the optimum water content.

Table 3. Properties of expansive soil in the CVS tests

Property	Nanning soil
Liquid limit, w_L(%)	48
Plastic limit, w_P (%)	21.4
Plastic index, I_P	26.6
Maximum dry density (Mg/m^3)	1.91
Optimum water content (%)	15

In the calculation of uplift friction using Eq. (7), compared with lateral swelling pressure (minimum 209.8kPa), the earth pressure at rest due to soil weight (maximum vertical pressure only reaches 12 kPa at a depth of 0.58m) is negligible. The shaft friction distribution curve was measured by Fan (2007), at the time when the soil in the test tank had be fully saturated. Figure 11 shows the comparison among the measured, simulated pile shaft friction distribution curve and estimated uplift shaft friction using Eq. (7). The results of this study are encouraging as the proposed method in this paper provides a more accurate estimation of the uplift shaft friction in comparison to fine element simulation results proposed by Fan (2007).

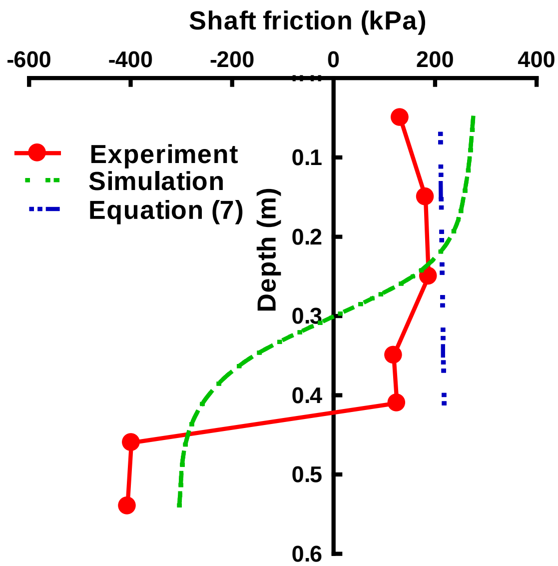


Figure 11. Comparison among pile shaft friction distribution curves

5 SUMMARY

There is limited understanding of how uplift friction generates along a pile in an unsaturated expansive soil in the literature. In this paper, the modified β method (Vanapalli and Taylan 2012) which is proposed for estimating the shaft friction along a pile in fine-grained soils using the mechanics of unsaturated soils is extended to estimate the uplift shaft friction in expansive soils by considering the influence of lateral swelling pressure. The proposed method is validated using the experimental results of a model pile conducted by Fan (2007). The method prosed in this study provides a reasonable estimation of the uplift shaft friction when the expansive soil is fully saturated from initial water content.

The proposed method is capable of estimating the variations of uplift shaft friction with respect to decreases in suction. However, due to lack of data, the variation of uplift shaft friction with respect to suction was not validated in this paper. Experimental studies in this direction are planned at the University of Ottawa to validate the proposed method. The proposed method is promising and can be promoted for the rational the design of pile foundations in expansive soil. However, more laboratory, field and numerical studies are required to fully validate the proposed method.

REFERENCES

Azam, S., Shah, I., Raghunandan M. E. and Ito M. (2013). "Study on swelling properties of an expansive soil deposit in Saskatchewan, Canada." *Bulletin of Engineering Geology*, 72(1): 25-35.

Alonso, E.E., Gens, A. and Joss, A.A. 1990. A constitutive model for partially saturated soils. *Geotechnique*, 1990, 40(3): 405-430.

Alonso, E.E., Vaunat, J. and Gens, A. 1999. Modelling the mechanical behaviour of expansive clays. *Engineering Geology*, 54: 173–183.

Basma, A.A., Al-Homoud, A.S. and Husein, A. 1995. Laboratory assessment of swelling pressure of expansive soils. *Appl. Clay Sci*, 9: 355-368.

Burland, J.B. 1973. Shaft friction of piles in clay- a simple fundamental approach. *Ground Engineering*, 6(3): 30-42.

Brackley, J.J.A. 1973. Swell pressure and free swell in a compacted clay. *Proceedings of the 3rd International Conference on Expansive Clays, Vol. 1*, Israel Institute of Technology, Haifa: 169-176.

Briaud, J.L., Zhang, X. and Moon, S. 2003. The shrink test–water content method for shrink and swell prediction. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 129(7): 590–600.

Chandler, R.J. 1968. The shaft friction of piles in cohesive soils in terms of effective stress. *Civil Engineering and Public Works Review*, 63: 48-51.

Chen, F.H. 1988. Foundations on expansive soils, Elsevier, New York.

Çimen, Ő., Keskin, S. N., and Yıldırım, H. 2012. Prediction of swelling potential and pressure in compacted clay. *Arabian Journal of Science and Engineering*, 37(6): 1535-1546.

Ertekin, Y. 1991. Measurement of lateral swell pressure with thin wall oedometer technique. *M.S. Thesis*, in Civil E ngineering, Middle East Technical University.

Fan, Z.H. 2007. Research on swelling-shrinkage characteristic and pile-soil interaction of expansive soil foundation. *PhD thesis*, Central south university. (In Chinese)

Fredlund, D.G. and Morgenstern, N.R. 1976. Constitutive relations for volume change in unsaturated soils. *Canadian Geotechnical Journal*, 13(3): 261-276.

Fredlund, D.G., Rahardjo, H. and Fredlund, M.D. 2012. Unsaturated Soil Mechanics in Engineering Practice, John Wiley & Sons, Inc., Hoboken, New Jersey.

Fredlund, D.G., Hasan, J.U. and Filson, H.L. 1980. The prediction of total heave. *Proceeding of 4th International Conference on Expansive Soils, ASCE and International Society for Soil Mechanics and Foundation Engineering*, Denver, 1-17.

Garven, E. and Vanapalli, S.K. (2006). Evaluation of Empirical Procedures for Predicting the Shear Strength of Unsaturated Soils. *Unsaturated Soils 2006*, 2570-2592.

Hamid, T.B. and Miller, G.A. 2009. Shear strength of unsaturated soil interfaces. *Canadian Geotechnical Journal*, 46 (5): 595-606.

Jennings, J.E.B. and Knight, K. 1957. The prediction of total heave from the double oedometer test. *Transact. S. African Inst. Civil Eng*, 7: 285-291.

Justo, J.L., Rodriguez, J.E., Delgado, A. and Jaramillo, A. 1984. A finite element method to design and calculate pier foundations in expansive soils. *In: Proceedings of Fifth International Conference on Expansive Soils*, Adelaide, Australia, 119-123.

Lytton, R.L., Aubeny, C. and Bulut, R. 2004. Design procedure for pavements on expansive soils. Report No. FHWA/TX-05/0-4518-1. *Texas Department of Transportation*, Austin, Texas

Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD). 2013. *Technical code for building in expansive regions*, China Architecture & Building Press, Beijing.

Navy, Department of Naval Faculities Engineering Command. 1971. *Design manual-soil mechanics* (DM 7.01). U.S. Department of the Navy, Alexandria, VA, 256.

Nelson, J.D., Chao, K.C., Overton, D.D. and Nelson, E.J. 2015. Foundation Engineering for Expansive Soils. John Wiley & Sons, Hoboken, New Jersey.

Rao, S.M. 2006. Identification and classification of expansive soils. Expansive Soils-Recent Advances in Characterization and treatment, Taylor & Francis, 15-24.

Sridharan, A., Rao, A.S. and Sivapullaiah, P.V. 1986. Swelling pressure of clays. *Geotechnical Testing Journal*, ASTM, 9(1): 24-33.

Vanapalli, S.K. and Lu, L. 2012. A state-of-the art review of 1-D heave prediction methods for expansive soils. *International Journal of Geotechnical Engineering*, 6(1): 15–41.

Vanapalli S.K. and Oh W.T. 2010. A model for predicting the modulus of elasticity of unsaturated soils using the soil-water characteristic curve. *International Journal of Geotechnical Engineering*, 4(4): 425-433.

Vanapalli, S.K. and Taylan, Z. 2012. Design of single piles using the mechanics of unsaturated soils. *Int. J. of GEOMATE*, 2(1): 197-204.

Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E. and Clifton, A.W. 1996. Model for the prediction of shear strength with respect to soil suction. *Canadian Geotechnical Journal*, 33(3): 379–392.

Vanapalli, S.K. and Fredlund, D.G. 2000. Comparison of empirical procedures to predict the shear strength of unsaturated soils using the soil-water characteristic curve. *The Proceedings of Unsaturated Soil sessions of Geo-Denver 2000*, Denver, 5–8 August 2000, 99: 195–209, American Society of Civil Engineers, Special Publication.

Wong, T.T., Fredlund, D.G. and Krahn, J. 1998. A numerical study of coupled consolidation in unsaturated soils. *Canadian Geotechnical Journal*, 35(6): 926–937.

Yin, Z.Z., H, Z. and Xu, G.H. 1994. Analysis and numerical simulations on deformations of soil-structure interface. *Chinese Journal of Geotechnical Engineering*, 16(3): 14-22.

Zhang, D., Liu, S. and Zhang, T. 2012. Water content and modulus relationship of a compacted unsaturated soil. *Journal of Southeast University (English Edition)*, 28(2): 209–214.