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Simplified Shear Deformation Method for Analysis of Mechanical Behavior of a Single Pile in Expansive Soils

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ABSTRACT: Seasonal volume changes associated with wetting and drying conditions due to infiltration and evaporation of water significantly influence the mechanical behavior of expansive soils. For this reason, rational design of foundations in expansive soils has been a challenge for the geotechnical engineers. Pile foundations have been found to be more suitable in carrying loads from the superstructure to the expansive soil below alleviating stability and deformation problems in comparison to other types of foundations. However, there is a lack of simple procedures in the literature to estimate how the load transfers from pile to the soil, which is the key information required in the rational design of pile foundations in expansive soils. In this paper, the conventional shear deformation method is modified to estimate the load transfer mechanism from pile to expansive soil taking account of the influence of infiltration and evaporation of water. The proposed approach is based on the mechanics of unsaturated soils and can be extended for single pile considering the influence of volume change behavior in expansive soils. In addition, parametric analysis undertaken in the present study suggests that the pile diameter and pile length significantly influence the mechanical behavior of piles in expansive soils. Geotechnical engineers can use the proposed method in routine design of foundations for expansive soils as the complexity associated with the estimation of pile mechanical behavior in expansive soils is significantly reduced.

KEYWORDS: Expansive soil, Unsaturated soil, Pile, Shear deformation method

1. INTRODUCTION

Vast deposits of expansive soils are widely distributed in several countries of six of the seven continents of the world. Some of these countries include Canada and United States from North America, Argentina from South America; Sudan and Algeria from Africa, China, India and Israel from Asia; Spain and United Kingdom from Europe and Australia from Australia (Chen 1988; Al-Rawas and Qamaruddin 1998; Rao et al. 2001). Expansive soils are typically referred to as problematic soils in the literature because their mechanical behavior is highly sensitive to the changes in their natural water content associated with environmental factors such as the infiltration and evaporation. Ground heave or settlement contribute to severe distress to various infrastructure constructed in expansive soils due to the changes in the natural water content that contribute to significant economic losses to building industry (Gourley et al. 1993; Jaremski 2012).

Of the various choices that are available as foundations for infrastructure placed in expansive soils, pile foundations are widely preferred (Al-Rawas and Goosen 2006). Several research studies suggest that piles can be used in expansive soils both in the form of micropiles or conventional piles. Micropiles control ground heave in the top layer of expansive soil in addition to providing support as foundation to the infrastructure constructed in expansive soils (Nelson et al. 2015). Small diameter steel piles (75 to 250mm in diameter) are typically inserted in predrilled holes of larger diameter, which are then filled with compacted sand to improve the frictional resistance of micropiles (Nusier and Alawneh 2004). Upon infiltration, expansive soils heave significantly reduces due to friction that mobilizes at the pile-soil interface. For this reason, micropile reinforcement technique is a rational choice to mitigate damages of lightly loaded structures in thin layer expansive soil deposits with limited swelling potential. However, for heavy structures on thick expansive soil layers, with high to very high swell potential, piles or group pile foundation are typically favored.

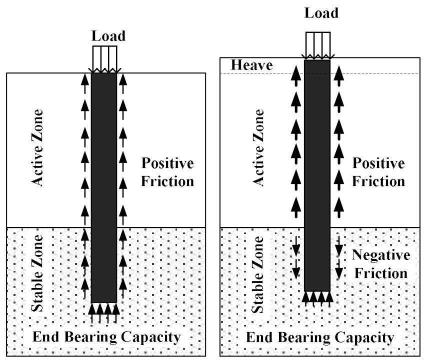
Piles with high strength and stiffness can penetrate through active zone (depth of expansive soil layer in which water content changes are sensitive to environmental factors associated with infiltration and evaporation) in expansive soil and are placed on rigid bedrock or lower stable soil stratum. Such a pile foundation system not only has a significant bearing capacity but also can effectively control the non-uniform settlement. Two kinds of pile foundations are commonly used in engineering practice; namely, single pile (drilled pile, pushing pile) (Poulos and Davis 1980; O'Neill 1988) or group pile foundation (helical pile, precast pile) (Ekshtein 1978; Blight 1984). Pile foundation with diameters greater than 800mm are typically cast in-situ. In some scenarios, in order to increase the bearing capacity of the pile foundation, belled pile with an enlarged base at the end is used. For enhancing integrity of group pile foundation, grade beams are used which link the pile top and form a pile grade beam foundation system. Such a pile system is more reliable to prevent the non-uniform settlement and tilt of the super structure.

In this paper, the traditional shear deformation method is modified for the estimation of the mechanical behavior of a single pile taking account of the influence of infiltration and evaporation in a typical expansive soil deposit, extending the mechanics of unsaturated soils. In other words, this method takes into account the seasonal ground heave and settlement due to the changes associated with the natural water content of expansive soils.

2. VARIATION OF LOAD TRANSFER MECHANISM OF PILE IN EXPANSIVE SOIL

The total bearing capacity of pile foundation conventionally comprises the contribution arising from two different components; namely, shaft friction and end bearing capacity for non-expansive soils. However, for expansive soils, contribution arising from each of the two components can vary significantly due to the swelling or shrinkage characteristics.

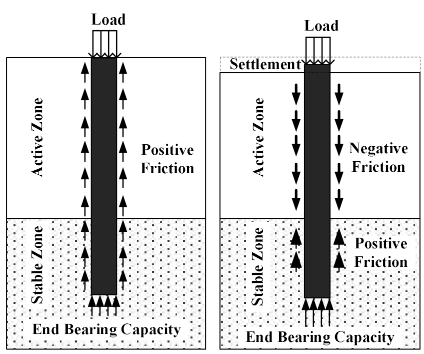
The variation of pile shaft friction and end bearing capacity for a pile in expansive soil prior to and after infiltration are shown in Figure 1(a) and Figure 1(b), respectively. Prior to water infiltration, positive friction arises along the entire length of the pile. Applied load is typically carried by shaft friction along the pile with some contribution arising from the pile end [as shown in Figure 1(a)]. However, as water infiltrates into the active zone, expansive soil swells. Positive friction changes in the active zone due to the mobilization of lateral swelling pressure and the reduction of the interface shear strength properties (Liu and Vanapalli 2017a). Typically, a pile placed under a lightly loaded structure may get uplifted due to the positive friction contribution, which is referred to as uplift friction. Once the pile has an upward movement, negative friction generates in the stable zone and the pile end bearing capacity decreases significantly. The net contribution that arises from negative shaft friction, end bearing capacity and applied load combined balance the increased uplift shaft friction.



(a) Before infiltration (b) After infiltration

Figure 1 Distribution of shaft friction along a single pile in expansive soil before and after infiltration

Due to the influence of evaporation conditions during dry season, there will be a decrease in the natural water content of expansive soil. As a consequence, expansive soil's volume shrinks, resulting in a further settlement of the ground surface. Negative friction arises in the active zone during this stage since soil moves downward relative to the pile foundation [as shown in Figure 2(a) and Figure 2(b)]. This phenomenon is opposite to that of infiltration which results in a reduction in both suction and lateral earth pressure due to the reduction in the lateral swelling pressure and increasing interface shear strength properties.



(a) Before shrinkage (b) After shrinkage

Figure 2 Distribution of shaft friction along a pile in expansive before and after evaporation

Several scholars investigated the mechanical behavior of pile foundations in expansive soils considering various approaches (Ekshtein 1978; Blight 1984; Fan 2007; Jaremski 2012; Justo et al. 1984; Nelson et al. 2015). This problem is typically analyzed using one of the two approaches: (i) Theoretical methods such as load transfer method proposed by Coyle and Reese (1966) and the shear deformation method proposed by Cooke (1974); (ii) Numerical simulation such as boundary element method (Poulos 1993) and finite element method (Nelson et al. 2012). Numerical simulation (including boundary element method and finite element method) is a robust option to model piles in expansive soils (Poulos 1993; Lytton 1977; Justo et al. 1984; Mohamedzein et al. 1999; Katona 1983; Desai et al. 1984; Mohamedzein and Nour Eldayem 2006; Al-Rawas and Goosen 2006). However, these approaches are time consuming as they are based on complex procedures and are not widely used in conventional engineering practice applications.

Fan (2007) presented an analytical solution to simulate the mechanical behavior of a single pile taking account of the influence of swelling and shrinkage characteristics of expansive soils extending superposition method to the traditional shear deformation method, which was originally proposed by Cooke (1974). This is a practical method that can be employed to obtain various distribution curves; which include pile head displacement, pile axial forces and skin friction along the pile shaft with the changes of vertical movements of the ground surface and loads on the pile top. However, this method requires solving several partial differential equations which are complex and hence not used widely in routine engineering practice. Liu and Vanapalli (2017b) more recently proposed a modified shear deformation method to determine how load transfers on the pile by dividing the pile into several segments to consider the influence of ground heave or ground settlement. However, to achieve an accurate solution, the pile needs to be divided into many segments which contributes to the calculation complexity. For these reasons, there is a need to propose a simple method for use in routine engineering practice applications.

3. PROPOSED METHOD

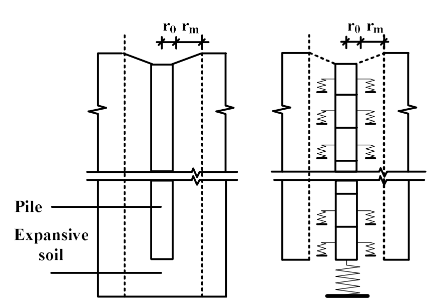
The conventional shear deformation method is modified in this paper for predicting the load transfer mechanism variation of single pile taking account of swelling and shrinkage characteristics in expansive soils extending the mechanics of unsaturated soils. In this method, the approach presented by Adem and Vanapalli (2016) has been extended for estimating expansive soil heave and settlement. The pile is assumed to be rigid; in other words, the deformation of pile body is negligible in comparison to the swelling and shrinkage of the expansive soil.

3.1 Basic assumptions

The following assumptions were used in the modification of simple shear deformation method: (i) There is no slip in the pile-soil interface; (ii) Compared with the heave and settlement of the pile, elastic deformation of pile body can be neglected; (iii) Expansive soil around the pile is assumed to be homogeneous, isotropic and linear elastic; (iv) Swelling and shrinkage of expansive soil are in elastic range and these two processes are reversible; (v) Expansive soil heave and settlement of the soil decrease linearly from the ground surface to the depth of active zone.

3.2 Simplified shear deformation method for single pile

In the traditional shear deformation method, the soil within the radius of influence r_m along with the soil under the pile end is assumed to be a series of springs (as shown in Figure 3). Extending theory of elasticity, the vertical settlement of soil surface at a depth z around the pile can be calculated using Eq. (1) and Eq. (2) (Coyle and Reese 1966).



(a) (b)

Figure 3 Analytical pile model used in the present study

$$w(z,r)=\frac{\tau_0 r_0}{G}\int_{r_0}^{\infty}\frac{\partial r}{r}=\frac{\tau_0 r_0}{G}\ln(\frac{r_m}{r}) \tag{1}$$

$$\begin{cases} w(z,r)=\dfrac{\tau_0 r_0}{G}\ln(\dfrac{r_m}{r}),\ r_0\le r\le r_m \\ w(z,r)=0,\ r>\mathrm{r_m} \end{cases} \tag{2}$$

where w = the vertical settlement of soil, G = the shear modulus of soil around the pile, r_0 = the radius of pile, r = the horizontal distance between the calculated point and the pile axis, r_m = the maximum influencing radius of pile on the soil, generally r_m can be estimated using Eq. (3) (Xiao et al. 2011).

$$r_m=2.5L(1-\upsilon_s) \tag{3}$$

where L is the length of the pile, υ_s = Poisson's ratio of the soil around the pile.

Eq. (2) can be modified as Eq. (4) to calculate the shaft friction along the pile.

$$\tau_0=w(z,r)\frac{G}{r_0}\ln^{-1}(\frac{r_m}{r_0})_s \tag{4}$$

Piles as foundation typically penetrate through the active zone of expansive soil layer and rest on bedrock or extend into soil layers with higher stiffness. In other words, mechanical behavior of the expansive soil under the pile base is no longer influenced by seasonal water content changes. However, possible movement of pile end caused by volume expansion or shrinkage of the expansive soil in the active zone can lead to changes in the contribution arising from end bearing capacity.

For piles that are placed on rigid bedrock, end bearing capacity contribution soon disappears when there is separation between the pile and bedrock. Such a scenario is likely due to the swelling of expansive soil which contributes to the lifting of the pile end, upon infiltration. However, due to evaporation effects, there can be negative friction that can arise in the active zone which can drag the pile end to rest on a rigid bedrock layer or stiff soil layer which can significantly increase the end bearing capacity contribution.

Randolph and Wroth (1978) extended the theory of elasticity concepts for soils to estimate the pile base settlement [Eq. (5)]

$$\begin{cases} \tau_b=k_{sb}\ w_b \\ k_{sb}=\dfrac{4\ G_{sb}}{\pi\ r_0(1-\upsilon_b)} \end{cases} \tag{5}$$

where τ_b = unit end resistance, w_b = pile-end settlement, k_{sb} = compressive rigidity of soil under pile end, G_{sb} = shear modulus of soil under pile end, υ_b = Poisson's ratio of soil under pile end, r_0 = pile radius.

Employing Eq. (4) and Eq. (5), the force equilibrium systems of a single pile under different scenarios are summarized in Figure 4. Figure 4(a) shows a scenario without any load applied on the pile top; for this case both the springs distributed along the pile shaft and the spring under the pile end is relaxed. Figure 4(b) shows under applied load P, the penetration of pile into the soil below the pile end is w_{z1}, corresponding stress state of the pile is described using Eq. (6). If the soil properties change with respect to depth within active zone and stable zone, layer wise summation method should be used.

$$\sum\frac{G}{r_0}\ln^{-1}(\frac{r_m}{r_0})w_{z1}\pi dL+k_{sb}w_{z1}\pi r_0^2=P \tag{6}$$

where P = the applied load, w_{z1} = the penetration of the pile into the soil [in the present study, downward penetration from the initial position is represented with positive value, as shown in Figure 4(a)], L = the pile length.

Typically, expansive soils in the active zone swell and result in ground surface heave upon water infiltration. Figure 4(c) and Figure 4(d) show expansive soils in the active zone heave of h_1 and h_2, respectively. The prediction equation by Adem and Vanapalli (2016) [i.e., Eq. (7)] can be used for calculation of heave in the active zone assuming the expansive soil is elastic in nature. In this study, within the active zone, the development of the heave is simplified as linear distribution as shown in Figure 5.

$$\Delta h=h\,[\frac{(1+\upsilon)(1-2\upsilon)}{E_a(1-\upsilon)}]\Delta(u_a-u_w) \tag{7}$$

where Δh = heave of soil, h = thickness of the calculated soil layer, E_a = average elastic modulus over the matric suction variation range, $\Delta(u_a - u_w)$ = variation in matric suction.

Several researchers during the last decade have focused to better understand the elastic modulus of unsaturated soils (Vanapalli and Oh (2010); Rahardjo et al. 2011; Zhang et al. 2012; Adem et al. 2014a; Lu and Kaya 2014). Adem and Vanapalli (2014b) extended the semi-empirical model for estimating modulus of elasticity of coarse and fine-grained unsaturated soils by Vanapalli and Oh (2010) for expansive soils. In this paper, the simple semi-empirical Eq. (8) developed by Adem and Vanapalli (2014b) is used to estimate the modulus of elasticity of unsaturated expansive soils, E_u. This equation suggests the E decreases with decreasing matric suction (i.e. during the infiltration process). In the calculation, E_a equals the average value of various E calculated using Eq. (8) over the matric suction variation range. The influence of mechanical stress (confinement) is neglected in this method. Such an assumption is conservative and can be extended in practice for lightly loaded residential structures and pavements where the soil matric suction changes have a predominant influence on the behavior of unsaturated expansive soils (Adem and Vanapalli, 2014b).

$$E_u=E_{sat}[1+\alpha\frac{(u_a-u_w)}{P_a/100}S^{\beta}] \tag{8}$$

where α and β = fitting parameters, Adem (2015) calculated E_u for five different expansive soils and suggested that β = 2 and α typically varies from 0.05 to 0.15 for expansive soils; P_a =atmospheric pressure.

Shear modulus can be deduced according to Eq. (9) from elastic modulus. Poisson's ratio of expansive soils, υ is usually assumed, estimated or measured from triaxial tests using the information of linear and lateral strain.

$$G_u=\frac{E_u}{2(1+\upsilon_s)} \tag{9}$$

where G_u = shear modulus of unsaturated soil.

Due to upward movement of the pile, the penetration of pile reduces to w_{z2} ($w_{z2} < w_{z1}$) in Figure 4(c) and w_{z3} ($w_{z3} < 0$) in Figure 4(d), corresponding stress state description of the pile is given in Eq. (10) and Eq. (11), respectively.

$$\Big[\sum \frac{G}{r_0}\ln^{-1}\Big(\frac{r_m}{r_0}\Big)\pi d L_s + k_{sb}\pi r_0^2\Big]\, w_{z2} + \sum \frac{G'}{r_0}\ln^{-1}\Big(\frac{r_m}{r_0}\Big)\pi d L_a\Big(w_{z2} - \frac{h_1}{2}\Big) = P$$

$$P > \sum \frac{G'}{r_0}\ln^{-1}\Big(\frac{r_m}{r_0}\Big)\pi d L_a \frac{h_1}{2},\ w_{z2} > 0 \tag{10}$$

$$\sum \frac{G}{r_0}\ln^{-1}\Big(\frac{r_m}{r_0}\Big)\pi d L_s w_{z3} + \sum \frac{G'}{r_0}\ln^{-1}\Big(\frac{r_m}{r_0}\Big)\pi d L_a\Big(w_{z3} - \frac{h_2}{2}\Big) = P, \tag{11}$$

$$P < \sum \frac{G'}{r_0}\ln^{-1}\Big(\frac{r_m}{r_0}\Big)\pi d L_a \frac{h_1}{2},\ w_{z3} < 0$$

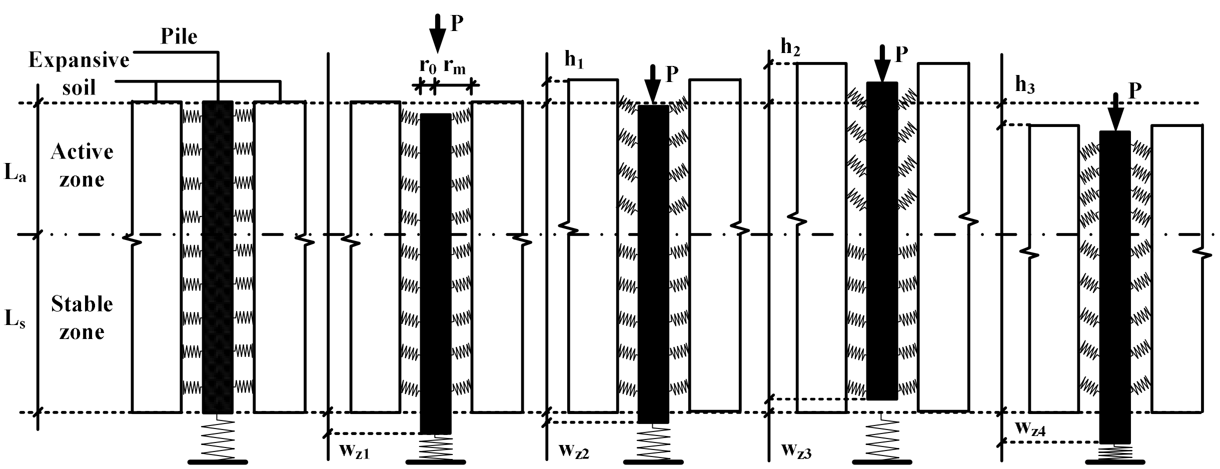
where G' = shear modulus of expansive soil changes with respect to matric suction, G = shear modulus of expansive soil in the stable zone, w_{z1} and w_{z2} = the penetration of the pile into the soil in Figure 4(c) and (d) respectively, h_1 and h_2 = heave of expansive soil within active zone in Figure 4(b) and (c) respectively [the initial position shown in Figure 4(a) highlights that there is an upward movement of soil and pile (heave) which is shown as a negative value while downward movement (shrinkage) is shown as a positive value], L_a = the pile length in the active zone, L_s = the pile length in the stable zone, $\sum \frac{G'}{r_0}\ln^{-1}\big(\frac{r_m}{r_0}\big)\pi d L_a \frac{h_1}{2}$ = total uplift force.

Expansive soils in the active zone undergo settlement, say h_3 due to evaporation effects as shown in Figure 4(e). For such a scenario, since soil in the active zone has a tendency to move downward relative to the pile, negative friction will be generated along the pile shaft. As a consequence , there is reduction in the bearing capacity

from pile shaft in the stable zone. The contribution from pile end bearing should have sufficient capacity to balance the increased downward force to alleviate foundation problems. Eq. (12) describes the stress state of the pile for this scenario. Also, it should be noted that the settlement upon evaporation h_3 is calculated using Eq. (7). This is reasonable as expansive soil is assumed to be elastic. The swelling ability of a typical expansive soil starts decreasing after a certain number wetting and drying cycles (Dif and Bluemel 1991; Estabragh et al. 2015). Some investigation studies suggest that predominant swelling or shrinkage occurs during the first wetting and drying cycle. However, volume change behavior significantly reduces after four or five wetting and drying cycles to attain equilibrium conditions (Al-Homoud et al. 1995; Basma et al. 1996). A summation method is more suitable as the mechanical properties of expansive soils vary significantly from the natural ground surface to the pile end. This method is also suitable for layered soils.

$$\Big[\sum \frac{G}{r_0}\ln^{-1}\Big(\frac{r_m}{r_0}\Big)\pi d L_s + k_{sb}\pi r_0^2\Big]\, w_{z4} + \sum \frac{G'}{r_0}\ln^{-1}\Big(\frac{r_m}{r_0}\Big)\pi d L_a\Big(w_{z4} - \frac{h_3}{2}\Big) = P \tag{12}$$

where w_{z4} ($w_{z4} > 0$) = the penetration of the pile into the soil in Figure 4(e), h_3 = the settlement of the expansive soil in Figure 4 (e).



(a) (b) (c) (d) (e)

Figure 4 Stress states of piles for different scenarios [(a) Without pile head load; (b) Under pile head load P; (c) Upon light infiltration and under pile head load P; (d) Upon heavy infiltration and under pile head load P; (d) Upon evaporation and under pile head load P]

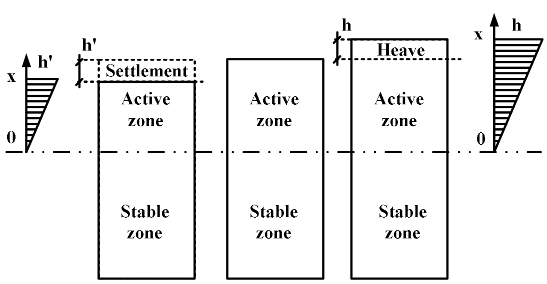


Figure 5 Linear reduction of heave and shrinkage with respect to depth

4. VERIFICATION OF PROPOSED METHOD

Limited laboratory investigations or field test data of pile foundations (i.e. single pile and group) performance in expansive soils are available in the literature. This may be attributed to the difficulties in conducting these studies taking into account of the influence of various parameters such as the lateral swelling pressure and soil suction. A laboratory study undertaken on a single model pile in an expansive soil subjected to infiltration is used in the validation of proposed method. Acceptable comparison was achieved between the experimental data (upward movement of the pile) and estimations made using the method proposed in this paper. These details are summarized below.

Figure 6 provides details of the model pile and test tank used in the study by Fan (2007). The tank was 0.9m in height and 0.5m in diameter. Three layers of different soils were filled in the test tank with 0.1m gravel in the bottom, 0.16m medium sand in the middle and 0.58m expansive soil in the top. Vertical and horizontal sand drains were distributed in the tank to facilitate the seepage of water. A 0.65m long PVC pipe filled with fly-ash inside was used as a model pile. A sand layer was adhered to the surface to create a rough surface. Strain gauges were installed at different depths along the length of the pile (as shown in Figure 6) so that the pile axial stresses can be back-calculated from the measured strains. An earth pressure cell was installed below the pile end to measure the end bearing capacity. Settlement of pile head and soil was measured using dial gauge that were placed at soil surface and at depth of 100 and 150mm below the surface. The pile end is placed on the sand layer.

Expansive soil used in this study is a compacted expansive soil that was collected from Nanning, Guangxi province in China. The soil properties are summarized in Table 1. The expansive soil was compacted with a degree of compaction higher than 90%.

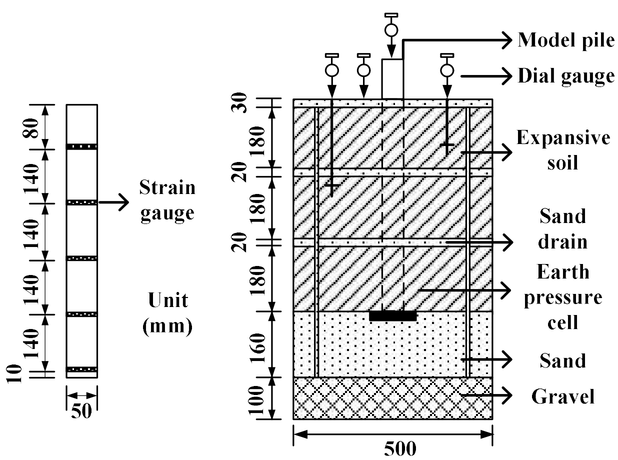


Figure 6 Sketch of the model pile and test tank in Fan's experiment (modified after Fan 2007)

Table 1 Properties of expansive soil in the test tank (from Fan 2007)

Property	Nanning soil
Liquid limit, w_L(%)	48.1
Plastic limit, w_P (%)	21.2
Plasticity index, I_P	26.9
Specific Gravity, G_s	2.74
Maximum dry density (Mg/m^3)	1.89
Optimum moisture content (OMC) (%)	15.8

Water was manually added to the expansive soil in the test tank such that the ground water table higher than the ground surface for about 400 hours. The measured heave associated with the infiltrated water into the expansive soil was 41.2mm and the upward movement of the pile was 3.59mm. Since there was no load applied on the pile top, Eq. (11) is suitable for analysis of this situation.

The elastic modulus measured at the optimum moisture content (15.8%) is 5.94MPa. As discussed earlier, elastic modulus of soil at unsaturated conditions are significantly higher than at saturated condition. In order to use Eq. (8), which is the semi-empirical equation for the calculation of elastic modulus at unsaturated condition, information of the soil water characteristic curve (SWCC) is required.

Fan (2007) conducted a series of constant volume swelling pressure tests using soil specimens compacted at different initial water contents. No swelling pressure was measured for the specimen compacted at an initial water content of about 26%. For this reason, this value of water content was assumed to be the saturated water content (at the degree of saturation of 100%). Fan (2007) also developed a finite element program to simulate the pile tests which showed good comparison with the experimental data. In this program, a new constitutive model was developed by modifying Barcelona Basic Model extending elastic-plastic models (Alonso et al. 1990). Parameters summarized in Table 2 used in Fan's program (2007) were also used in this study (Liu and Vanapalli 2017a). The SWCC used in this program is shown in Figure 7.

From measured heave values of expansive soil at different depth (as shown in Figure 8), the active depth was approximately estimated to be 330mm as no heave was measured at this depth level.

Table 2 Elastic parameters required in the calculation of Eq. (10)

Property	Nanning soil
Elastic modulus at optimum water content, E_o (MPa)	5.94
Elastic modulus at saturation, E_{sat} (MPa)	0.89
Shear modulus at optimum content, G_o (MPa)	2.29
Shear modulus at saturation, G_{sat} (MPa)	0.34
Poisson ratio, υ	0.30

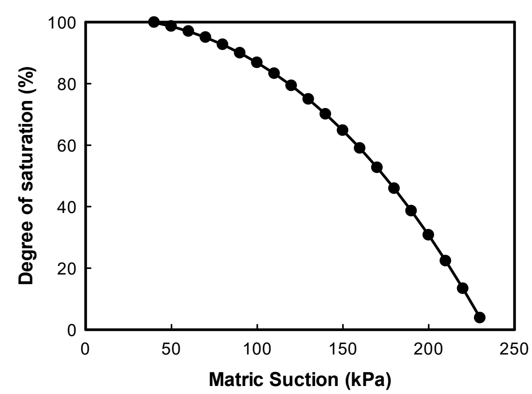


Figure 7 SWCC used in the program proposed by Fan (2007)

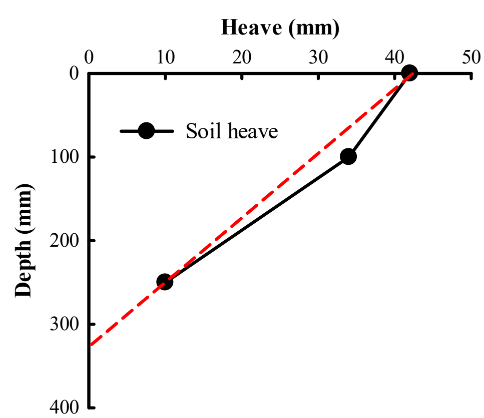


Figure 8 Heave of soil at different depths (Modified after Fan 2007)

Comparison between the experimental data, prediction by Fan (2007), simulation by Fan (2007) and prediction using Eq. (11) are summarized in Table 3. These results suggest that the method proposed in this paper provides an acceptable estimation of the pile upward movement. Errors associated with using this method can be attributed to the deformation of the pile body, which is assumed to be negligible. However, the proposed method significantly reduces the complexity in spite of sacrificing some accuracy.

Table 3 Comparison of measured and predicted heave

Method	Pile heave (mm)
Fan (2007), Experiment	3.59
Fan (2007), Finite element program	5.71
Proposed method	**3.40**

5. PARAMETRIC ANALYSES

An example problem is presented for parametric analysis to study the influence of pile diameter and pile length on the shaft friction distribution, end bearing capacity and pile head settlement of a single pile taking account of the influence of infiltration and evaporation conditions.

A single pile is assumed to be constructed in Regina expansive clay as shown in Figure 9. Regina expansive clay deposit is 9m thick and has an active zone of 5m. Details of pile diameters, pile lengths used for performing parametric analyses are summarized in Table 4.

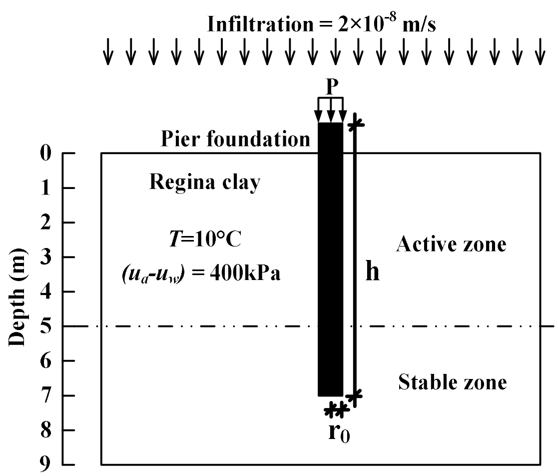


Figure 9 Assumed pile foundation and group pile foundation in Regina expansive clay (Modified after Adem 2015)

Table 4 Summary of pile parameters used in the analysis

Pile case	Pile diameter (m)	Length of pile (m)	Pile distance (m)	Applied load (kN)
Pile (1)	**0.8**	7	-	2000
Pile (2)	**0.9**	7	-	2000
Pile (3)	**1**	7	-	2000
Pile (4)	0.8	**8**	-	2000
Pile (5)	0.8	**9**	-	2000

Regina clay was chosen as a candidate material in the present study because it was also modelled by other investigators (Vu and Fredlund, 2006 and Adem, 2015). The soil properties of Regina clay are summarized in Table 5.

Table 5 Properties of Regina expansive clay (modified after Adem 2015)

Soil properties	Values
Atterberg limits	w_l = 69.9%, w_p = 31.9%, I_p = 38%
Unified Soil Classification System	CH, Inorganic clay of high plasticity
Specific gravity	G_s = 2.83
Maximum dry unit weight	γ_{dmax} = 14.01 kN/m^3
Optimum water content	w_{optm} = 28.5 %
Swelling index	C_s = 0.088
Corrected swelling pressure	P_s = 300 kPa
Total unit weight	γ_t = 17.27 kN/m^3
Initial void ratio	e_0 = 0.955
Saturated modulus of elasticity	E_{sat} = 1100 kPa
Poisson's ratio	μ = 0.4
Saturated coefficient of permeability	k_{sat} = 0.00523 m/day
Saturated volumetric water con	θ_s = 0.5015
Initial matric suction	$(u_a - u_w)_i$ = 400 kPa

5.1 Infiltration and evaporation conditions

To study the influence of infiltration on the mechanical behavior of single pile, an infiltration of 2×10^{-8} m/s was imposed on the ground surface around the structure for a period of 175days. The soil-water characteristic curve (SWCC) for Regina clay shown in Figure 10 is given by Vu (2002) using the experimental data measured by Shuai (1996). The permeability function (k function) estimated by Adem (2015) using the software VADOSE/W with the input information of the saturated coefficient of permeability (0.00523m/day = 6.053× 10^{-8}m/s) and the SWCC from Vu (2002) are used in this study.

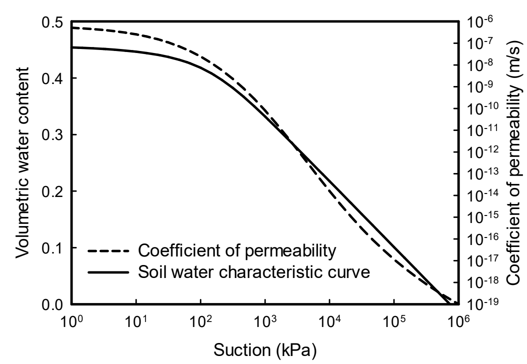


Figure 10 Soil water characteristic curve and coefficient of permeability of Regina clay used in the example problem (Modified after Vu 2002)

Figure 11 shows the variation of matric suction profiles in response to infiltration and evaporation conditions. In this study, only the final phase after infiltration for 175days is analyzed, for which ground surface heave of 36mm was modeled by Adem (2015) using Eq. (7). A simple situation (as shown in Figure 11) is assumed for the dry season (to represent evaporation conditions). The matric suction in the active zone is assumed to increase linearly in the active zone depth. The matric suction at ground surface is 900kPa which reduces linearly to a value of 400kPa where the active zone ends. In this study, the swelling and shrinkage of expansive soil are assumed to be in elastic range and are reversible. The ground settlement due to the matric suction increment from initial state to the matric suction upon evaporation can be also calculated using Eq. (7). In the calculation of unsaturated elastic modulus using Eq. (8), the fitting parameter β = 2 and α = 1/9 used by Adem (2015) are also adopted in this study. The ground surface settlement of 26mm is estimated using Eq. (7).

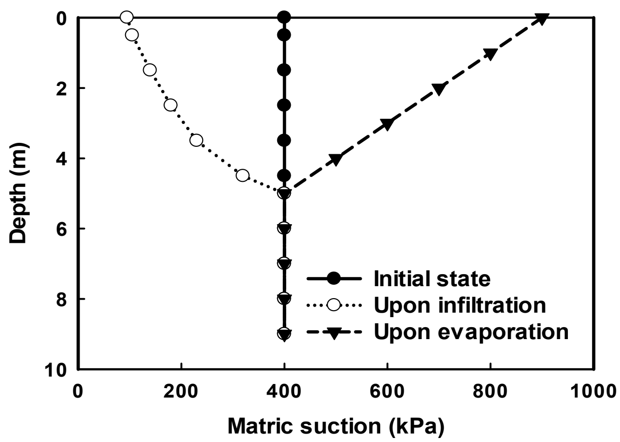


Figure 11 Variation of matric suction profile due to the influence of infiltration and evaporation

5.2 Influence of pile diameter

It is assumed that a load of 2000kN is applied on the single piles of different diameters. The free ground heave and settlement can be calculated using Eq. (7) for the matric suction variation associated with infiltration and evaporation conditions shown in Figure 11.

Figure 12 summarizes the results of how pile-soil relative displacement, end bearing capacity and shaft friction vary due to infiltration and evaporation conditions for different pile diameters. The pile-soil relative displacement upon infiltration and evaporation are shown in Figure 12(a) and (b), respectively. The pile shaft friction distribution upon infiltration and evaporation are shown in Figure 12(c) and (d), respectively. The pile end bearing capacity shown in Figure 12(e) is calculated using Eq. (5). The pile head settlement shown in Figure 12(f) is calculated using Eq. (10).

The pile shaft friction [as shown in Figure 12(c)] has a value greater than the stable zone due to the influence of infiltration because of the larger pile-soil relative displacement in the active zone [see Figure 12(a)]. During dry season, negative friction [as shown in Figure 12(d)] arises near the ground surface due to the relative downward movement of soil in comparison to the pile [see Figure 12(b)]. In Figure 12(b), the pile-soil relative displacement gradually decreases with depth. When the settlement of pile and soil are same, there is no shaft friction. This depth is defined as the neutral point. Below the neutral point, positive shaft friction generates and offers resistance to the settlement of pile. From Figure 12(e), in comparison to the initial state without infiltration or evaporation, the end bearing capacity is less significant during infiltration and more significant during evaporation. The pile settlement associated with infiltration and evaporation conditions are shown in Figure 12(f). The pile experiences a positive settlement during infiltration stage because of the uplift force that generates in the active zone is less than the applied load. The pile experiences a more significant settlement upon evaporation because of negative friction generation in the active zone.

The pile shaft friction increases along the entire pile length; however this increase is more pronounced in piles of lesser diameters due to influence of infiltration as shown in Figure 12(c). The small diameter pile can generate a lower negative shaft friction but a larger positive shaft friction [see Figure 12(d)]. Also, the depth of neutral point increases with increasing pile diameter. Figure 12(e) illustrates that end bearing capacity of larger diameter pile is more significant. Figure 12(f) suggests that the settlement of pile increases with increasing pile diameter both for infiltration and evaporation conditions. In conclusion, for single pile, the degree of mobilization of pile shaft friction increases with decreasing pile diameter while the mobilization of pile end bearing capacity decreases during this process.

5.3 Influence of pile length

As shown in Figure 13, for the same load of 2000kN applied on the pile top, the short pile can generate more significant shaft friction as well as end bearing capacity. The settlement of pile decreases with an increase in the pile length. During this process, the depth of neutral point also increases as well. In conclusion, with an increase in pile length, there will be a decrease in the mobilization of both pile shaft friction and end bearing capacity.

6. CONCLUSIONS

Pile foundations are widely used in expansive soils for carrying loads from the superstructure alleviating stability and deformation problems. However, in many scenarios there are several problems with the performance of super-structure or sub-structure (i.e., pile foundations) placed in expansive soils due to the influence of seasonal volume changes which contribute to swelling and shrinkage characteristics. The load transfer mechanism of pile foundation can experience significant changes with respect to the volume changes of expansive soil. Simple techniques are not available for practicing engineers to take into account of these parameters and propose rational design of pile foundations in expansive soils. In this paper, a simplified shear deformation method is proposed to analyze the load transfer mechanism for pile foundations taking account of the influence of infiltration and evaporation conditions based on the mechanics of unsaturated soils. In this method, it is assumed that the deformation of the pile body is negligible compared to the ground surface displacement. The heave of a single pile upon infiltration is estimated using the proposed method for a model pile test investigated by Fan (2007) in a laboratory environment. There is an acceptable agreement with the experimental data presented by Fan (2007). More filed case studies are necessary for the verification and further improvement of proposed method.

Furthermore, parametric analysis is conducted to study the influence of pile diameter and pile length on the mechanical behavior of single pile (including shaft friction distribution, end bearing capacity and pile head settlement). The results suggest that for single pile, the degree of mobilization of pile shaft friction increases with decreasing pile diameter; however, the mobilization of pile end bearing capacity decreases. With an increase in pile length, mobilization of both pile shaft friction and end bearing capacity decreases.

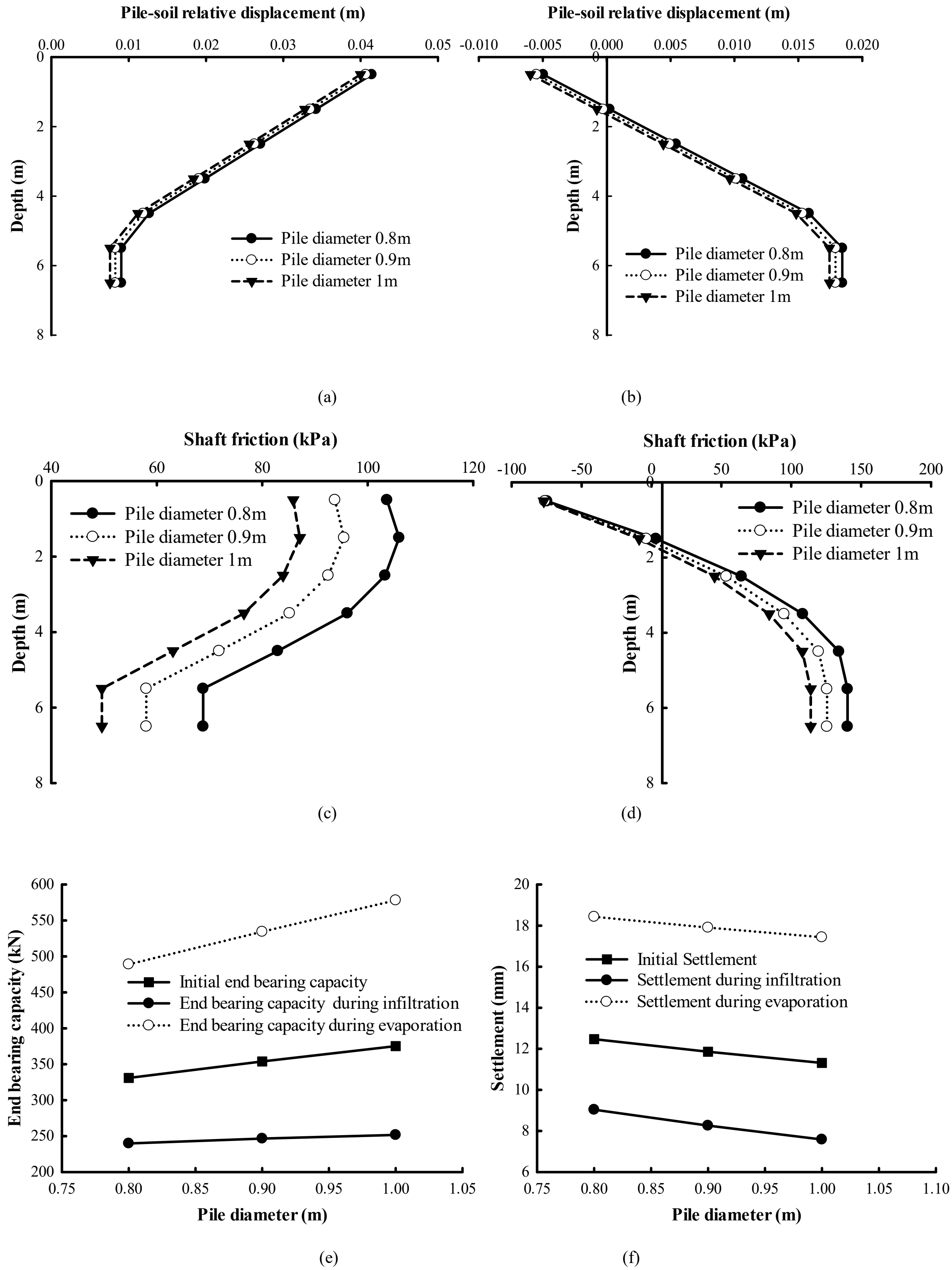


Figure 12 Influence of pile diameter: (a) Pile-soil relative displacement during infiltration; (b) Pile-soil relative displacement during evaporation; (c) Shaft friction distribution during infiltration; (d) Shaft friction distribution during evaporation; (e) Variation of end bearing capacity during infiltration and evaporation; (f) Settlement of pile during infiltration and evaporation

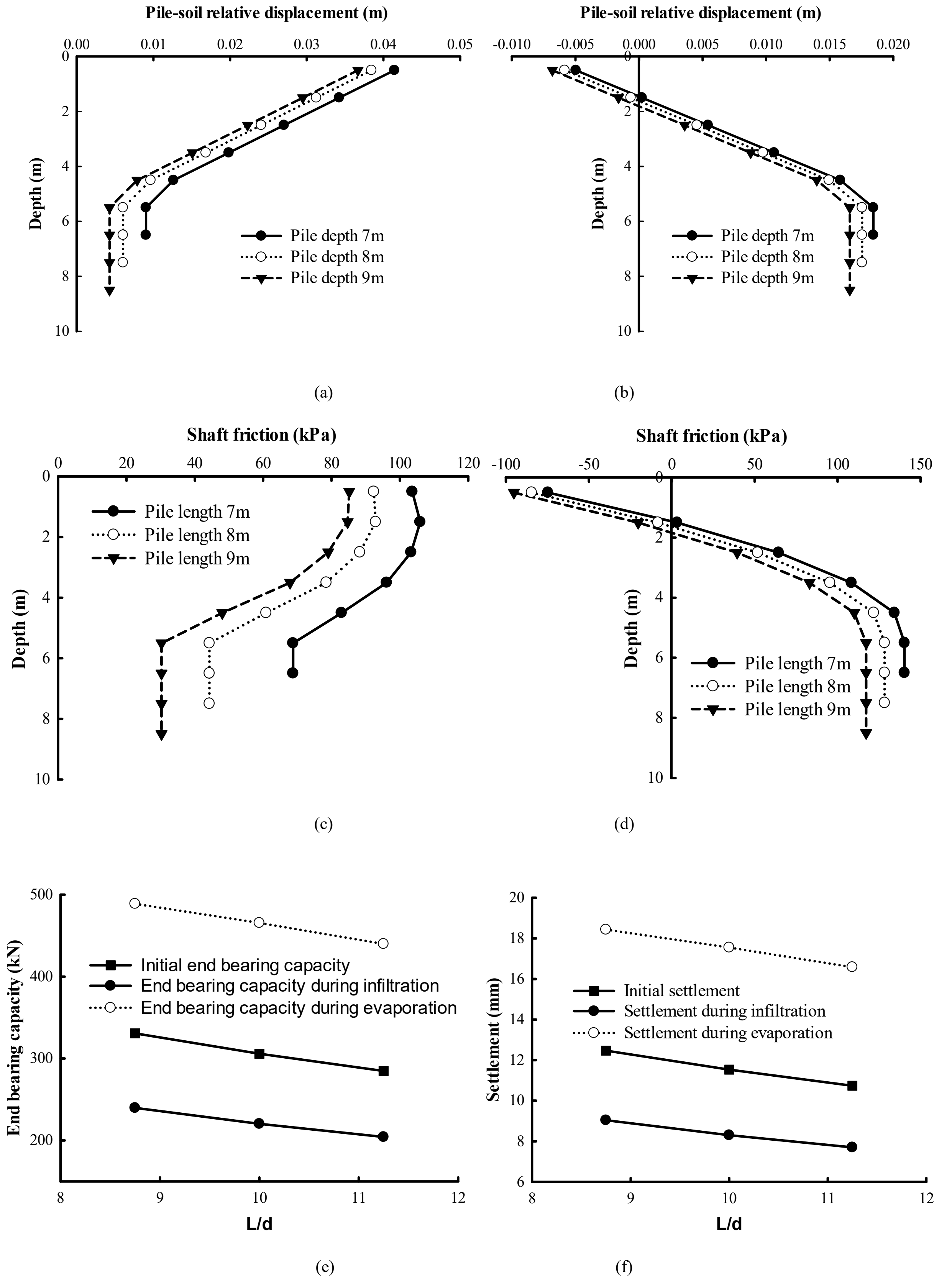


Figure 13 Influence of pile length: (a) Pile-soil relative displacement during infiltration; (b) Pile-soil relative displacement during evaporation; (c) Variation of shaft friction during infiltration; (d) Shaft friction distribution during evaporation; (e) Variation of end bearing capacity during infiltration and evaporation; (f) Settlement of pile during infiltration and evaporation

7. REFERENCES

Adem, H.H., and Vanapalli, S.K. (2014a) "Elasticity moduli of expansive soils from dimensional analysis". Geotechnical Research, 1(2), 60-72.

Adem, H.H., and Vanapalli, S.K. (2014b) "A simple method for prediction of the modulus of elasticity of unsaturated expansive soils". Proceedings of UNAST2014 Conference, Unsaturated Soils: Research and Application, Sydney, Australia.

Adem, H.H. (2015) "Modulus of elasticity based method for estimating the vertical movement of natural unsaturated expansive soils". PhD thesis, University of Ottawa, Ottawa, Canada.

Adem, H. H., and Vanapalli, S. K. (2016) "Heave prediction in a natural unsaturated expansive soil deposit under a lightly loaded structure". Geotechnical and Geological Engineering, 34(4), 1181-1192.

Alonso, E.E., Gens, A., and Josa, A.A. (1990) "A constitutive method for partially saturated soils". Géotechnique, 40(3), 405-430.

Al-Rawas, A. A., and Qamaruddin, M. (1998) "Construction problems of engineering structures founded on expansive soils and rocks in northern Oman". Building and Environment, 33, 159-171.

Al-Rawas, A. A., and Goosen, M. F. A. (2006) "Expansive soils: Recent advances in characterization and treatment". Taylor & Francis, London, UK.

Al-Homoud, S., Basma, A., Malkawi, H., and Bashabsheh, A. (1995) "Cyclic swelling behaviour of clays." Journal of Geotechnical Engineering, 121(7), 562-565.

Blight, G.E. (1984) "Uplift forces measured in piles in expansive clay". Proceedings of the 5th International Expansive Soils Conference, Adelaide, 1, pp240-244.

Basma, A.A., Al-Homould, A.S., Husein, M., and Ai-Bashabsheh, M.A. (1996) "Swelling-shrinkage behavior of natural expansive clays." Applied Clay Science, 11(2-4), 211-277.

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

Cooke, R.W. (1974). "The settlement of friction pile foundations". Proceeding of Conference on Tall Buildings, Kuala Lumpur, Malaysia.

Coyle, H. M., and Reese, L.C. (1966) "Load transfer for axially loaded piles in clay". Journal of the Soil Mechanics and Foundation Engineering, 92(2), 122-126.

Desai, C. S., Zaman, M. M., Lightner, J. G., and Siriwardane, H. J. (1984) "Thin-layer elements for interfaces and joints". International Journal for Numerical and Analytical Methods in Geomechanics, 8(1), 19-43.

Dif, A. E., and Bluemel, W. F. (1991) "Expansive soils under cyclic drying and wetting." Geotechnical Testing Journal, Technical Note, 14(1), 96-102.

Ekshtein, L.I. (1978) "Investigation of the uplift of pile groups in swelling soils". Translated from Osnovaniya, Fundamenty i Mekhanika Gruntov, 3, 16-17.

Estabragh, A. R., Parsaei, B., and Javadi, A. A. (2015) "Laboratory investigation of the effect of cyclic wetting and drying on the behaviour of an expansive soil." Soils and Foundations, 55(2), 304-314.

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

Gourley, C.S., Newill, D., and Schreiner, H.D. (1993) "Expansive soils: TRL's research strategy". Proceedings of the 1st International Symposium on Engineering Characteristics of Arid Soils, London, UK.

Jaremski, J. (2012) "Application of the joining pile for foundations on expansive clays and rocks". American International Journal of Contemporary Research, 2(10), 53-58.

Justo, J.L., Rodriguez, J.E., Delgado, A., and Jaramillo, A. (1984) "A finite element method to design and calculate pile foundations in expansive soils". Proceedings of Fifth International Conference on Expansive Soils, Adelaide, Australia, pp119-123.

Katona, M. G. (1983) "A simple contact-friction interface element with applications to buried culverts". International Journal for Numerical and Analytical Methods in Geomechanics, 7(3), 371-384.

Liu, Y., and Vanapalli, S. K. (2017a) "Influence of Lateral Swelling Pressure on the Geotechnical Infrastructure in Expansive Soils". Journal of Geotechnical and Geoenvironmental Engineering, 143(6), 04017006.

Liu, Y., and Vanapalli. S.K. (2017b) "Modified shear deformation method for analyzing the load-displacement response of a single pile in expansive soil upon infiltration". Proceeding of 70th Canadian Geotechnical Conference, Ottawa, Canada.

Lu, N., and Kaya, M. (2014) "A power law for elastic moduli of unsaturated soil". Journal of Geotechnical and Geoenvironmental Engineering, 140(1), 46-56.

Lytton, R.L. (1977) "Foundations in expansive soils". In: Desai, C.S. and Christian, J.T, Editors. Numerical methods in geotechnical engineering. New York: McGraw Hill Book Company, pp370-474.

Mohamedzein, Y. E-A., Mohamed, M.G., and EI Sharief, A.M. (1999) "Finite element analysis of short piles in expansive soils". Computer and Geotechnics, 24, 231-243.

Mohamedzein, Y. E. A., and Nour Eldayem, F. E. (2006) "The effect of interface on the performance of piles in expansive soils". Proceeding of 10th Arab Structure Engineering Conference, Kuwait University, Kuwait, pp13-15.

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, USA.

Nusier, O.K., and Alawneh, A.S. (2004) "Micropile technique to control upward movement of lightweight structures over expansive soils". Geotechnical and Geological Engineering, 22, 89-104.

Nelson, J., Thompson, E., Schaut, R., Chao, K., Overton, D., and Dunham-Friel, J. (2012) "Design procedure and considerations for piles in expansive soils". Journal of Geotechnical and Geoenvironmental Engineering, 138(8), 945-956.

O'Neill, M. W. (1988) "Adaptive model for drilled shafts in expansive clay". In Special Topics in Foundations, ASCE, pp 1-20

Poulos, H. G., and Davis, E. H. (1980) Pile foundation analysis and design, Wiley, New York, USA.

Poulos, H. (1993) "Piled Rafts in swelling or consolidating soils". Journal of Geotechnical Engineering, 119(2), 374-380.

Rao, S. M., Reddy, B. V. V., and Muttharam, M. (2001) "The impact of cyclic wetting and drying on the swelling behavior of stabilized expansive soils". Engineering Geology, 60, 223-233.

Randolph, M.F., and Wroth, C.P. (1978) "Analysis of deformation of vertically loaded piles". Journal of Geotechnical and Geoenvironmental Engineering, 104, 1465-1488.

Rahardjo, H., Melinda, F., Leong, E.C., and Rezaur, R.B. (2011) "Stiffness of a compacted residual soil". Engineering Geology, 120(1-4), 60-67.

Shuai, F. (1996) Simulation of swelling pressure measurements on expansive soils. Ph.D. thesis. University of Saskatchewan, Saskatoon, Canada.

Vu, H.Q. (2002) Uncoupled and coupled solutions of volume change problems in expansive soils. Ph.D. thesis. Department of Civil Engineering, University of Saskatchewan, Saskatoon, Canada.

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

Vu, H.Q., and Fredlund, D.G. (2006) "Challenges to modelling heave in expansive soils". Canadian Geotechnical Journal, 43(12),1249–1272.

Xiao, H., Zhang, C., Wang, Y., and Fan, Z. (2011) "Pile-Soil Interaction in Expansive Soil Foundation: Analytical solution and numerical simulation". International Journal of Geomechanics, 11(3), 159-166.

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.