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Simple Approaches for The Design of Shallow and Deep Foundations for Unsaturated Soils II: Numerical Techniques

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Abstract. Numerical techniques are widely used in conventional engineering practicefor obtaining the stressversus settlement or load versus displacement (P – δ) behavior, respectively and use the information in the design of shallow and deep foundations, extending the principles of saturated soil mechanics. This Companion Paper II summarizes the details of numerical techniques that can be used in the design of shallow and deep foundations in unsaturated soils. The two key properties required for performing the numerical techniques are the shear strength and the modulus of elasticity of unsaturated soils. A user-friendly subroutine (USDFLD) has been developed for use in the commercial software, ABAQUS to predict the variation of these soil properties with respect to matric suction. The only additional information required for performing the numerical modeling in addition to the conventional soil properties is the soil-water characteristic curve (*SWCC*). Good agreements were observed between the proposed numerical techniques and from theoretical approaches and experimental studies. The numerical techniques discussed in this paper are simple and can be used by the geotechnical engineers in the design of shallow and pile foundations 20 in unsaturated soils.

Keywords: numerical modeling, unsaturated soil, load-settlement behavior, bearing capacity, shallow foundation, deep foundation

1 Introduction

Various types of shallow and deep foundations are designed as sub-structures to carry loads from the superstructure to the soil below alleviating problems associated with bearing capacity and settlement behavior of soils. The load-displacement behavior, which is vital information for the design of foundations are significantly influenced by the shear strength properties and modulus of elasticity of the soil. In many scenarios, foundations are placed in unsaturated soils; hence, soil suction has a significant influence on the bearing capacity and settlement behavior of soils. During the last few decades, several experimental studies that include laboratory and field investigations were undertaken to understand the influence of matric suction on the performance of shallow and deep foundations in unsaturated soils [for example, 1-13]. Some of these investigations also focused on developing theoretical approaches for interpreting the bearing capacity and settlement behavior of unsaturated soils that were discussed in the Companion Paper I. These studies provided valuable information for understanding the bearing capacity of foundations in both unsaturated coarse and fine-grained soils extending modified effective stress approach (MESA) and modified total stress approach (MTSA).

Numerical techniques have been widely used in the design of foundations because of their advantages associated with low costs for saturated soils [14-16]. However, in the last 20 years, there is significant interest towards developing numerical methods for unsaturated soils [7, 9, 17-20]. For example, Oh and Vanapalli [21, 22] simulated the bearing capacity of shallow foundations in unsaturated soils extending the MESA using Sigma/W [23]. The results validate the numerical modeling method extending the FEA using the elastic-perfectly plastic model. There is a good comparison between the measured vertical stress and settlement behavior for a model footing tested in the unsaturated sand and numerical results. Han et al. [24] conducted numerical analysis with Plaxis [25] to investigate the stress and settlement relationship of shallow foundation on sand. The numerical results are consistent with the FEA results carried out by Oh and Vanapalli [21] with Sigma/W. Oh and Vanapalli [26]conducted FEA on shallow foundations in fine-grained soils extending the MTSA with Sigma/W. The results of this study suggest that the foundation bearing capacity increases with an increase in Poisson's ratio; however, the bearing capacity is not influenced significantly by the earth pressure coefficient, K. Al-Khazaali et al. [27] and Han and Vanapalli[28] conducted FEA using Plaxis to simulate the $P – \delta$ behaviour of single pile in unsaturated soils. The influence of matric suction on the shear strength, elastic modulus and shear strength of pile-soil interface were considered in the FEA. These studies suggest that the bearing capacity and slope of $P – \delta$behavior of the model pile largely increases with increasing matric suction.

The above studies show that the Sigma/W and Plaxis can provide reasonable results for estimating the bearing capacity of shallow and deep foundations in unsaturated soils. This paper explores the feasibility of ABAQUS to simulate the behavior of foundations on unsaturated soils. ABAQUS has advantages of providing several user-friendly subroutines and has large-scale computational capacities to solve complex nonlinear problems. In this Companion Paper II, numerical simulations were performed to investigate the stress versus settlement or load versus displacement ($P – \delta$) behavior of shallow and deep foundations in unsaturated soils, respectively. A code is written based on the theoretical approaches discussed in the Companion Paper I and used in the subroutine USDFLD of ABAQUS to model the non-linear behavior of shear strength and modulus of elasticity of unsaturated soils. The results from the numerical models are compared with the theoretical approaches and experimental studies and are discussed for their strengths and limitations. The various numerical studies summarized in this companion paper are promising for use in geotechnical engineering practice for the design of foundations in unsaturated soils.

2 Numerical Techniques

The soil shear strength and elastic modulus are the two key properties required in the design of a foundation for determining the bearing capacity and settlement, respectively. Both the soil shear strength and elastic modulus vary nonlinearly with matric suction in unsaturated soils. Vanapalli et al. [29]proposed shear strength prediction equations using the saturated shear strength parameters of the soil and the soil water characteristic curve (*SWCC*) (i.e., Eq. 1a and 1b). Eq. 1a and 1bare respectively more suitable for coarse- and fine-grained soils [29-31].

$$\tau = c' + \left(\sigma_{\mathrm{n}} - u_{\mathrm{a}}\right)\tan\phi' + \left(u_{\mathrm{a}} - u_{\mathrm{w}}\right)(S^{\kappa})\tan\phi' \qquad (1a)$$

$$\tau = c' + \left(\sigma_{\mathrm{n}} - u_{\mathrm{a}}\right)\tan\phi' + \left(u_{\mathrm{a}} - u_{\mathrm{w}}\right)\left(\frac{\theta - \theta_{\mathrm{r}}}{\theta_{\mathrm{s}} - \theta_{\mathrm{r}}}\right)\tan\phi' \qquad (1b)$$

where c' and ϕ' are the effective shear-strength parameters of the saturated soil, τ is the shear strength of unsaturated soil, S is the degree of saturation, u_a is air pressure and u_w is water pressure, $u_a - u_w$ is soil suction and ($\sigma - u_{\mathrm{a}}$) is net normal stress, θ, θ_{s} and θ_{r} are respectively the volumetric water content of the soil, the saturated volumetric water content and residual volumetric water content, κ is the fitting parameter.

Eq. 1a and1b, [$c' + (\sigma - u_{\mathrm{a}}) \tan\phi'$] represents the saturated shear strength. The terms, [($u_a - u_w$) $S^{k}\tan\phi'$] and [($u_a - u_w$) (($\theta - \theta_r$)/$\theta_s - \theta_r$) $\tan\phi'$] in Eq. 1aand1b,represent the contribution of the matric suction towards the shear strength. Several studies suggest the effective internal friction angle, ϕ' is not influenced by the matric suction in the soil; for 80 this reason, the total cohesion (i.e., apparent cohesion, c_{a}) of the unsaturated soil can be expressed as

$$c_a = c' + \left(u_{\mathrm{a}} - u_{\mathrm{w}}\right)(S^{\kappa})\tan\phi' \qquad (2a)$$

$$c_a = c' + \left(u_{\mathrm{a}} - u_{\mathrm{w}}\right)\left(\frac{\theta - \theta_{\mathrm{r}}}{\theta_{\mathrm{s}} - \theta_{\mathrm{r}}}\right)\tan\phi' \qquad (2b)$$

The variation of undrained shear strength of fine-grained soils with respect to suction can be predicted using the 84 equation (Eq. 3)below

$$c_{\mathrm{u(unnsat)}} = c_{\mathrm{u(sat)}}\left[1+\frac{(u_{\mathrm{a}} - u_{\mathrm{w}})}{(P_a/100)}(S^{\nu})/\mu\right] \tag{3}$$

where $c_{\mathrm{u(unsat)}}$, $c_{\mathrm{u(sat)}}$are the shear strength under saturated and unsaturated conditions, respectively. ν and μ are fitting parameters. ν is determined by the soil type and μ is related to the soil plasticity index [32]. Oh and Vanapalli [32] proposed Eq. 4 for interpreting and predicting the variation of modulus of elasticity for unsaturated soils (i.e. E_{unsat}). In addition to the *SWCC*, the information required for predicting E_{unsat} include saturated modulus of elasticity (i.e. E_{sat}) and two fitting parameters, α and β. α value is related to the ratio of footing size to soil particle size[33] and β is a parameter that is related to soil type, normally β =1 for coarse grained soils[33] and β =2 [34] for fine-grained soils.

$$E_{\mathrm{unsat}} = E_{\mathrm{sat}}\left[1+\alpha\frac{(u_{\mathrm{a}}-u_{\mathrm{w}})}{(P_a/101.3)}\left(S^{\beta}\right)\right] \tag{4}$$

where $P_{\mathrm{a}}$is the atmosphere pressure (101.3kPa).

Eq. 2 and 3were included into the Mohr-Coulomb model for estimating the variation or unsaturated soil properties with matric suction for modeling the behavior of shallow and deep foundations in unsaturated soils. For achieving this, a code was specially written and included into subroutine USDFLD, which is a special feature that can be used with ABAQUS [35]. The USDFLD facilitates to calculate the material properties taking account of the influence of field variables such as pore water pressure at various coordinates of element nodes. In other words, it derives the solutions from the previous increment and updates the influence of field variable into the current increment.This feature is a valuable tool to describe reliably the non-linear behavior of unsaturated soils taking account of the influence of matric suction.

3 Numerical Modeling

3.1 Shallow foundations on unsaturated coarse-grained soil

A numerical finite element analysis (FEA) study is conducted with ABAQUS in this paper and compared with the experimental model footing test results on a 100mm × 100mm square footing on Unimin sand performed by Mohamed and Vanapalli [39]. In addition, the FEA results are also compared with the results using MESA proposed byOh and Vanapalli[21]. The details of the experimental studies and the MESA are summarized in the first companion paper. For a better comparison, the settings in the numerical model are similar to an earlier study conducted by Oh and Vanapalli[21].

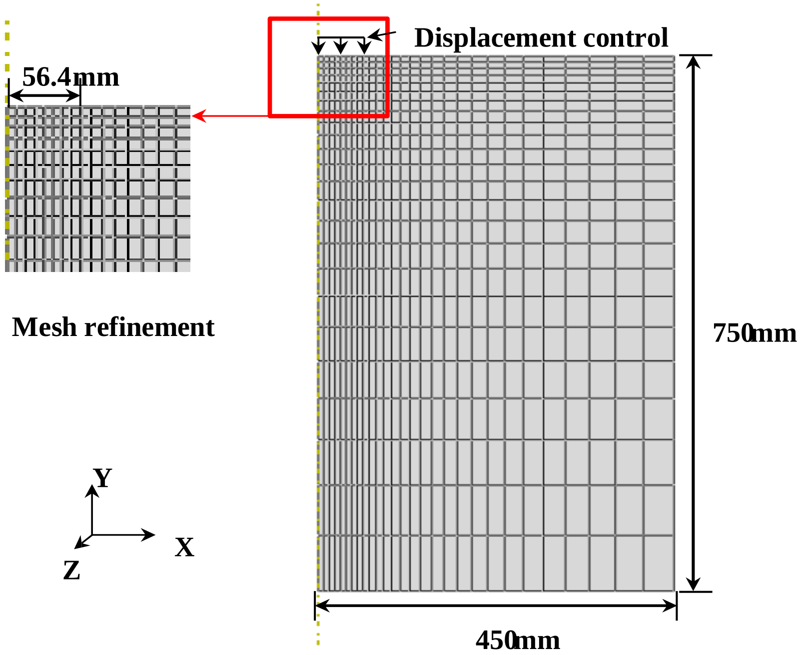


Fig. 1. Numerical model details in ABAQUS for Unimin sand

Axisymmetric model has been set up in ABAQUS shown as Figure 1. In the numerical model, circular model footing with a diameter, *D*, of 56.4mm is used to replace the square model footing with the same area (100mm × 100mm) used in the model footing test performed by Oh and Vanapalli [21]. Soil dimension (750mm Height, 450mm Radius) is the same as that used in the experiments and is large enough to avoid the boundary effects. Parametric studies for three average matric suction (0 kPa, 2 kPa, 4 kPa) were considered in the numerical modeling. The average matric suction is the centroid of the matric suction distribution profile in the stress bulb zone beneath the foundation (which is at a depth of 1.5B or 1.5D). The matric suction distribution profiles are assumed to be linear along the depth above water table under hydrostatic conditions (with a value of -$\gamma_{water}h_{unsat}$, h_{unsat} is the height above the ground water table). The Unimin sand used in the numerical model is simulated as an elastic-perfectly plastic material following the modified Mohr-Coulomb (M-C) model. The soil properties are summarized in Table 1. The elastic modulus is the same as that used by Oh and Vanapalli[21]. As discussed earlier, user subroutine USDFLD facilitates to model the variation of soil cohesion respect to matric suction of the unsaturated soils. The cohesion of the soil is estimated using Eq. 2a with κ =1 for sand. The dilatancy angle is estimated as 10% of the effective friction angle [36].

Table 1. Properties of Unimin sand used in the numerical model

Property	Value
Specific gravity, G_s	2.65
Dry density, γ_d (kN/m^3)	16.05
Saturated effective cohesion, c' (kPa)	0.60
Effective internal friction angle ϕ' (˚)	35.3
Dilatancy angle ψ (˚)	3.53
Poisson’s ratio, υ	0.3
Saturated elastic modulus, E_{sat}(kPa)	2659
Average elastic modulus at suction of 2 kPa (kPa)	11250*
Average elastic modulus at suction of 4 kPa (kPa)	16875*

* Evalue is the same as that used by Oh and Vanapalli[21]

A 4-node bilinear axisymmetric quadrilateral hybrid integration mesh (CAX4H) has been used in the model. Due to the high plastic strain of soil near the edges of the footing, a more refined mesh was used near the footing as shown in Figure 1. Horizontal constraint has been added along the vertical boundaries of the model. The bottom boundary is fixed. Displacement control of 20mm has been applied at the soil surface beneath the foundation for the bearing capacity analysis.

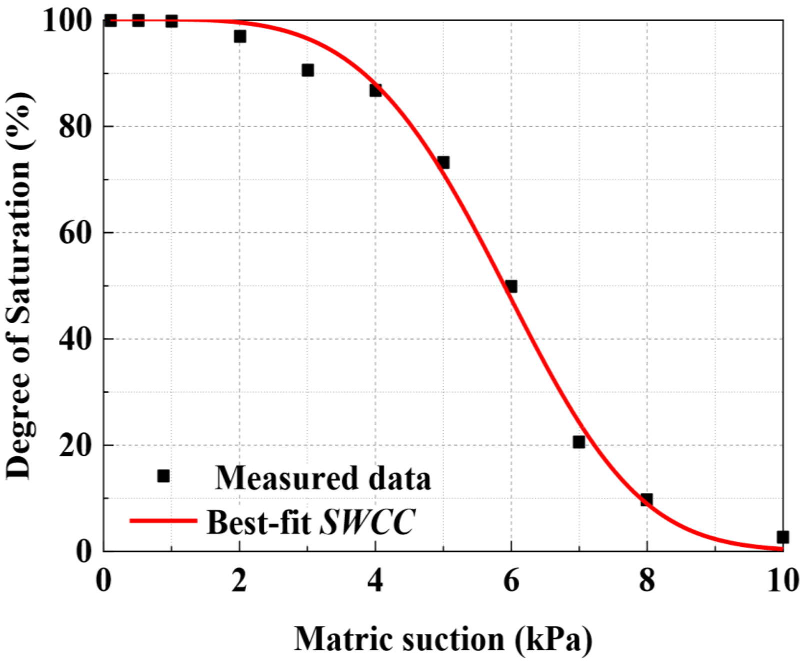


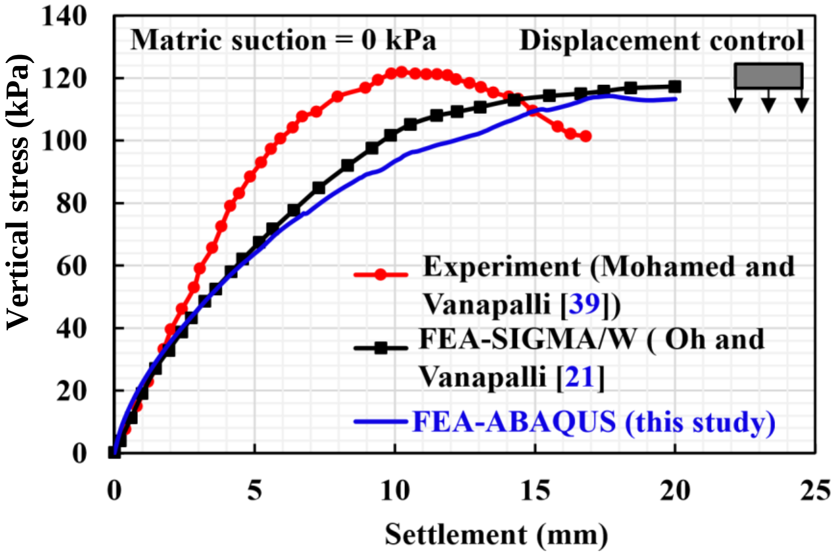
Fig. 2.*SWCC* of the Unimin sand

The *SWCC* of the Unimin sand is shown in Figure 2. The measured data are from the experimental results fromVanapalli et al. [37]. The best-fit *SWCC* was obtained using the Fredlund and Xing's [38] equation

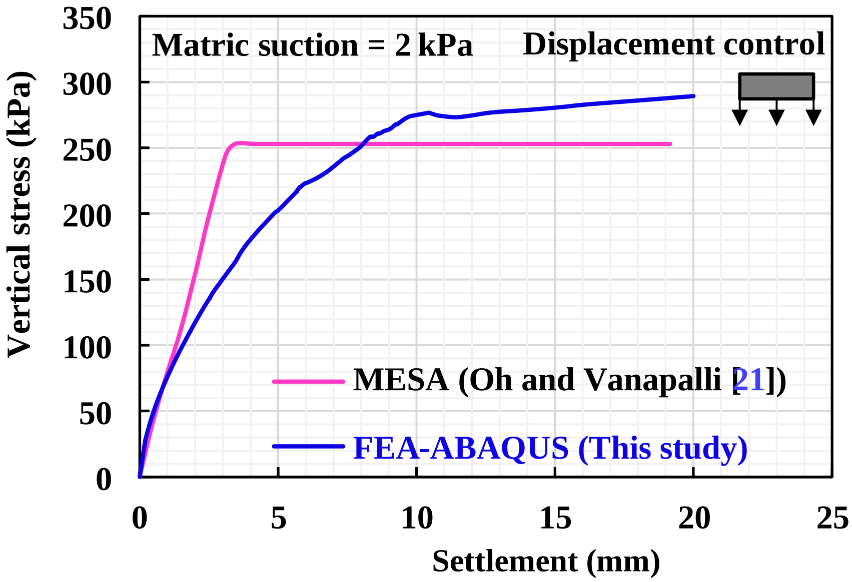
$$S=\left[C(\psi)\right]\left[\frac{1}{\ln\left(e+\left(\frac{\psi}{\alpha}\right)^{n}\right)}\right]^{m} \qquad (5)$$

$$C(\psi)=\frac{\ln\left(1+{}^{(\psi)}\!/_{(\psi)_r}\right)}{\ln\left[1+(1000000/(\psi)_r)\right]}$$

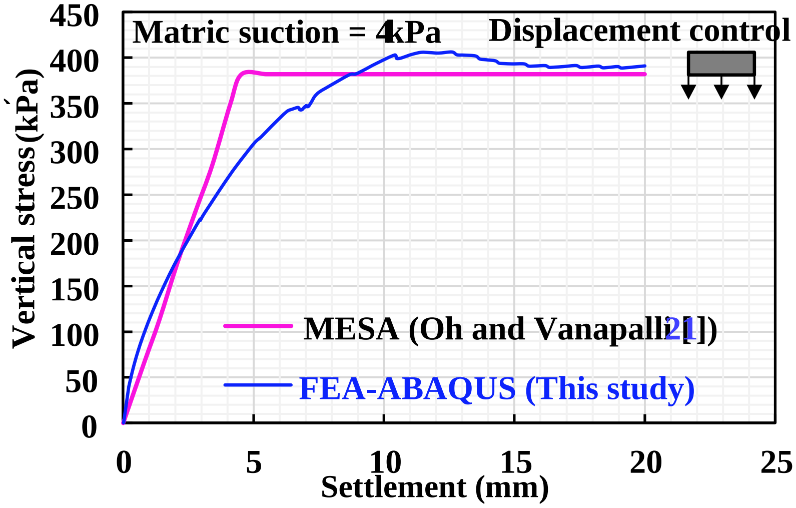
where $C(\psi)$ is the correction function, ψ represents the matric suction. $e$is Euler's number with 2.718, α, n and m are fitting parameters with values of 16.673, 4.341 and 177.270 [37], respectively.



(a) Vertical stress versus settlement behavior of foundation under saturated condition



(b)Vertical stress versus settlement behavior of foundation under average suction of 2 kPa



(C)Vertical stress versus settlement behavior of foundation under average suction of 4 kPa

Fig. 3. Comparison of vertical stress versus settlement behavior of foundation for various matric suction values

Results of the vertical stress versus settlement behavior under different matric suction values are shown in Figure 3. Comparisons have been made between the results from FEA and that from different methods [21, 39].Figure 3a shows the vertical stress versus settlement behavior of foundation on saturated soil. It can be seen that the stress versus settlement behavior of the foundation from the numerical modeling (SIGMA/W and ABAQUS) are similar. The results of FEA are conservative compared with measured values by Mohamed and Vanapalli [39]. This may be attributed to the stress versus strain behavior during the experiments will be influenced by several factors in addition to the parameters used in the numerical technique. However, the FEA are reasonable and reliable towards providing foundation stress versus settlement behavior.

Figure 3b and 3c represent the vertical stress versus settlement behavior of foundation with average matric suction values of 2 kPa and 4 kPa. The results from the FEAare close to the results from the MESA by Oh and Vanapalli[21]. Such a behavior may be attributed to the assumed linear elastic-perfectly plastic behavior extending MESA and similar criteria used in the ABAQUS. The bearing capacity from the FEA and that from the MESA are compared in Figure. 4.It can be seen that the deviation between the bearing capacity derived from FEA and that estimated using MESA are within the deviation line of 20% that suggests the method used in the FEA is reliable. The bearing capacity of the foundation at an average matric suction of 4 kPa is approximately four times of that at saturated condition. These results suggest that even minor differences in matric suction values can contribute to significant differences to the estimated foundation bearing capacity. In other words, matric suction is a sensitive parameter that influences the foundation bearing capacity in coarse-grained soils.

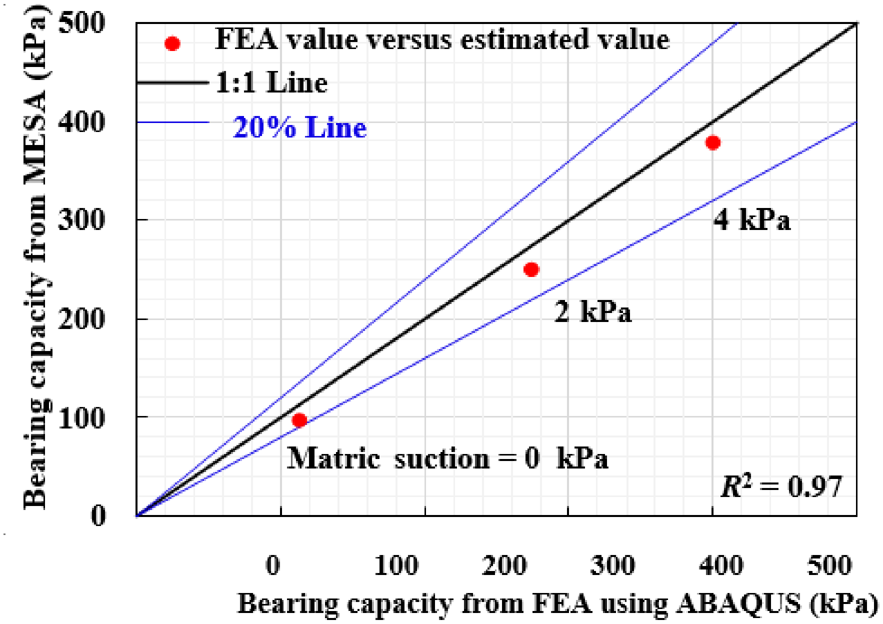


Fig. 4. Comparison between the bearing capacity from FEA and that estimated from MESA

3.2 Shallow foundation on unsaturated fine-grained soil

FEA has been conducted in this study on Indian Head till (IHT), which is a fine-grained soil from Saskatchewan, Canada to investigate the bearing capacity of strip foundation. The parametric studies on foundation bearing capacity include four different ground water tables. Four uniform suction distribution profiles (Suction=55, 100, 160, 200 kPa) and four linear suction distribution profiles (Figure 5)corresponding to the four ground water table depths (2m, 4m, 8m, 12m) were considered. Comparisons between the results of FEA and that estimated from theoretical study, MTSA, proposed by Vanapalli et al. [40] are provided.

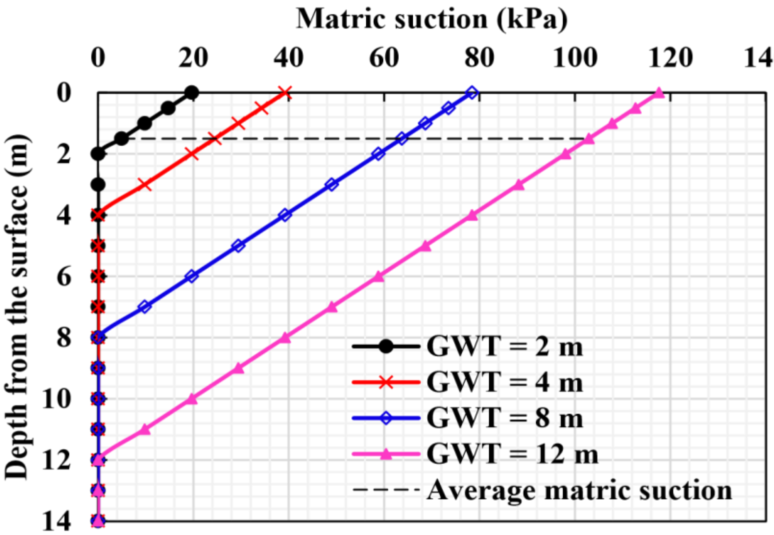


Fig. 5. Initial linear suction distribution profile for different ground water tables

Plain strain model has been set up in ABAQUS as shown in Figure 6. The strip foundation with a width of 2 m was modeled as a rigid body in the numerical model with an elastic modulus of 20MPa and a Poisson's ratio of 0.2. The soil dimension is 12m × 14m (Width × Height) and the ratio of width of the soil (12m) to the width of the foundation (2m) is 6, which is consistent with the experimental program conducted by Oh and Vanapalli [6]. The soil is simulated as an elastic-perfectly plastic material using modified M-C model. Table 2 summarizes soil properties used in the numerical model based on the properties provided by Oh and Vanapalli [26]. Estimation of c_{unsat} and $E_{unsat}$are based on Eq. 3 and Eq. 4. The fitting parameters of $v = 2$, $\mu = 10$ have been used to calculate c_{unsat}in Eq. 3. Fitting parameters of α=0.1 and β=2 were used in Eq. 4 for E_{unsat}.

Table 2..Properties of Indian Head till used in the numerical model

Property	Value
Specific gravity, G_s	2.72
Dry density, γ_d (kN/m^3)	13.92
Saturated undrained shear strength, $q_u/2$ (kPa)	13.1
Saturated elastic modulus, E_{sat}(MPa)	3516
Poisson's ratio, υ	0.37

A 4-node bilinear plane strain quadrilateral hybrid integration mesh (CPE4H) has been used in the numerical model. Mesh refinement has been conducted near the footing due to the high plastic strain of soil near the edges of the footing shown in Figure 6. The 'general contact' has been used to simulate the interface between the footing and the soil. Horizontal constraint has been added along the vertical boundaries of the model; in addition, the bottom boundary is fixed. Displacement control of 1m has been applied at the reference point at the bottom of the foundation for bearing capacity analysis.

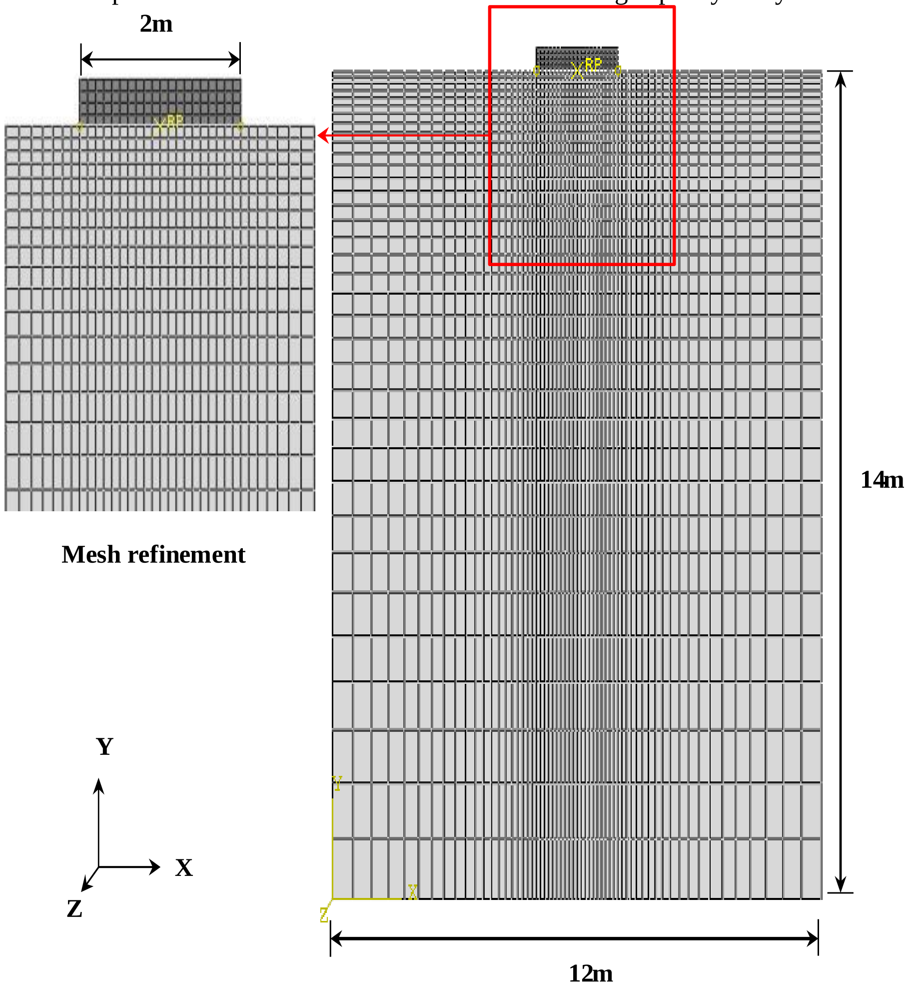


Fig. 6. Numerical model details used in ABAQUS for Indian Head till

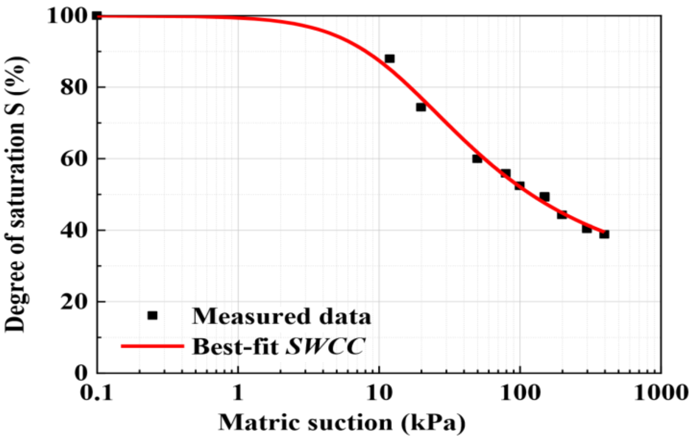
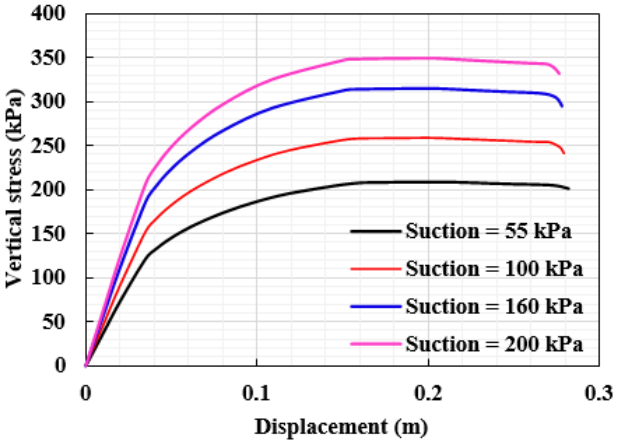


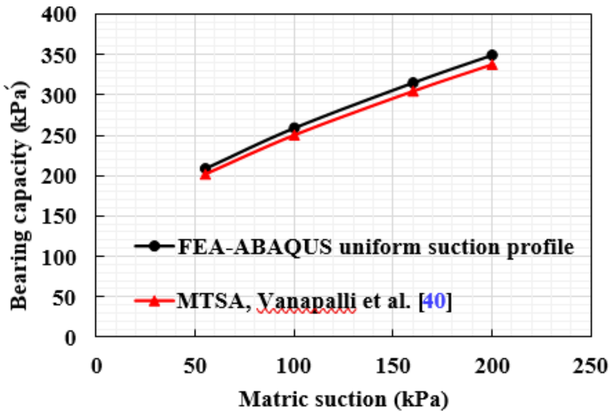
Fig. 7. *SWCC* of Indian Head till

The *SWCC* of the IHT is shown in Figure 7. Measured data are obtained from Oh and Vanapalli [26]. Van Genuchten(VG) [41] model with effective degree of saturation S_e (Eq. 6) has been used to fit the curve with fitting parameters of a = 0.084, n = 1.478 and the residual degree of saturation S_r = 0.256.

$$S_e = \frac{S - S_r}{1 - S_r} = \left\{ \frac{1}{1 + \left[\alpha \left(u_a - u_w \right) \right]^n} \right\}^{(n-1)/n} \tag{6}$$



(a) Vertical stress versus displacement behavior of foundation



(b) Variation of bearing capacity with respect to matric suction from ABAQUS and MTBA

Fig. 8. Summary of results of foundation behavior in unsaturated fine-grained soil with uniform suction distribution using ABAQUS and MTSA

Figure 8 shows the results of foundation stress versus displacement behavior and bearing capacity variation for uniform suction distribution profiles. As expected, higher matric suction contributes to a higher bearing capacity. The bearing capacity of the foundation at matric suction of 200 kPa is about 1.5 times that of matric suction of 55 kPa in Figure 8b. Comparison between the results from the FEAand that estimated from the MTSA is less than 3.5%, suggesting the numerical modeling results are reasonable.

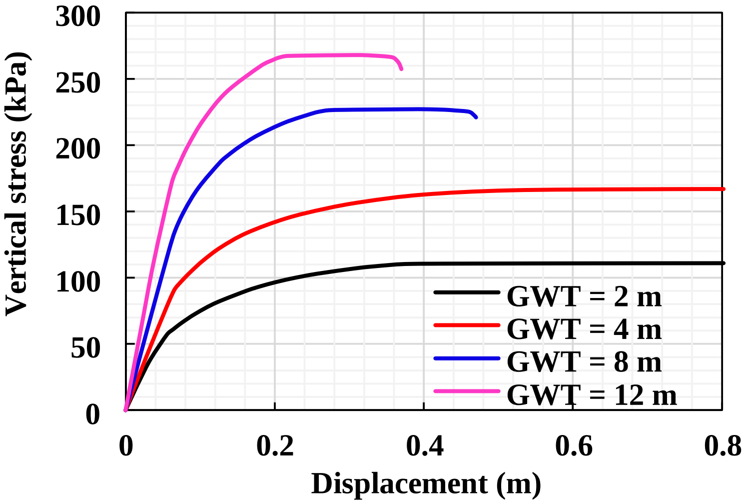


Fig. 9. Vertical stress versus displacement behavior of foundations under linear suction distribution.

Figure 9summarizes the results of the foundation vertical stress versus settlement behavior under linearmatric suction distribution profiles. The deeper ground water table provides a relative higher matric suction and contributes to a higher elastic modulus. The higher elastic modulus is typically associated with higher ultimate bearing capacity along with a lower vertical displacement. Figure 10 shows the variation bearing capacity of foundations for different four ground water table conditions. The bearing capacity of foundation with ground water table of 12m is almost 2.5 times of that with ground water table of 2m.

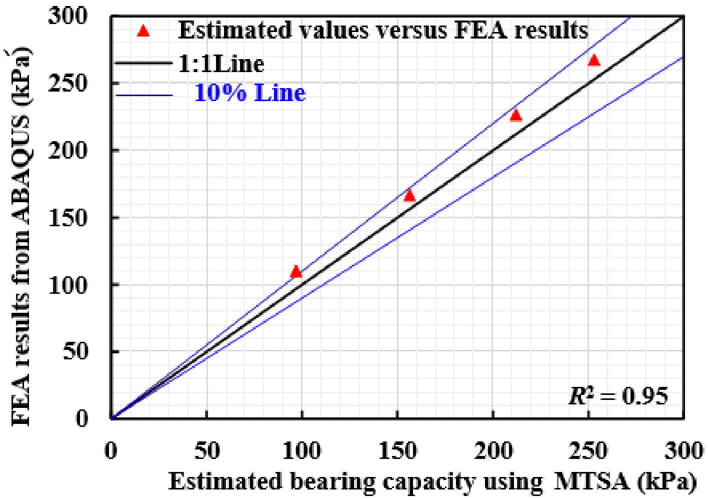


Fig. 10. Comparison between the bearing capacity results from ABAQUS and that derived from MTSA

Comparisons are also made between the foundations bearing capacity estimated from the MTSA and that from the FEA. It can be seen from Figure 10 that the results of FEA are higher in comparison to the MTSA. The maximum deviation from the FEA results to that from MTSA is around 13%, the other deviations are all less than 10%. The relative large deviation is found at ground water table of 2m which is lower than the depth (*H*) of the plastic zone below the foundation, about 1.5*B* (*B*=2m, therefore *H*=3m). The average matric suction in the stress bulb below the foundation used for bearing capacity estimation is based on the method proposed by Oh and Vanapalli [6]. The method was extended for the scenario of ground water table that was greater than the stress bulb.The estimation of the average matric suction for GWT = 2 m can be divided into two parts, the first part of it is above the ground water table with linear matric suction distribution and the second part is below the ground water table with uniform matric suction of zero. This leads to an underestimation of average matric suction in the stress bulb and results in the lower predicted bearing capacity compared to that from FEA. This also explains why the deviation of results from uniform suction profile (3.4% mentioned above) is lower than that from the linear suction distribution curve; that is due to the deviation of average matric suction in the uniform suction profile is rather small.

3.3 Pile foundation in unsaturated coarse-grained soils

The $P - \delta$ behavior of single model piles in unsaturated coarse-grained soils (i.e., Unimin Sand) were investigated using FEA by Vanapalli et al. [10]. Half of the pile-soil system was analyzed considering the symmetry. The model dimensions and details are illustrated in Figure 11.

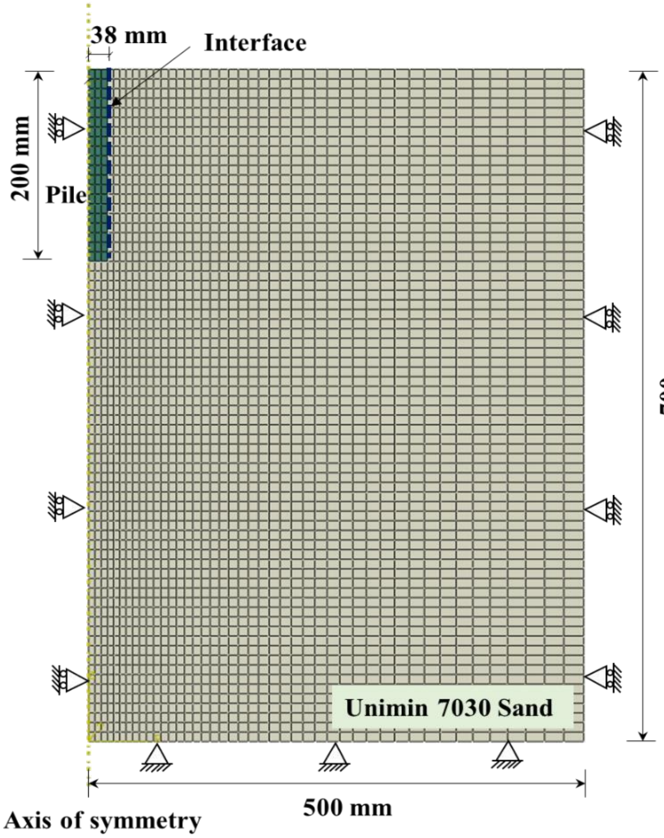


Fig. 11. Details of finite element model

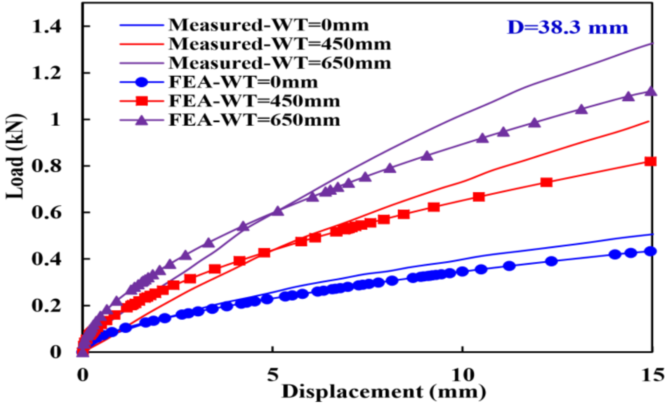
Single piles with three different diameters (i.e., 38.3 mm, 31.75 mm, 19.25 mm) with a length of 200 mm were modelled as linear-elastic materials. The pile modulus of elasticity E_p = 20 GPa and the Possion's ratio, υ= 0.15 was used in the model. TheUnimin sand was modelled as an elastic perfectly plastic material using a modified M-C constitutive model extended to unsaturated conditions. The apparent cohesion, $c_a$was derived from matric suction profile using saturated shear strength parameters (Eq. 2) and *SWCC* (Eq. 5). A user-defined subroutine as discussed for shallow foundations was implemented in modified M-C model to describe the mechanical behavior of unsaturated soils. The unsaturated modulus of elasticity,E_{unsat} was determined using Eq. 4. The average matric suction values of 2 and 4 kPa were used with the corresponding water levels at 450 mm and 650 mm depth, respectively.Since the sand is non-plastic material, the fitting parameterβ=1 was used in Eq. 4. Oh et al. [33]suggested that α values ranged from 0.5 to 2.5 based on the foundation size. α =1 was chosen to provide reasonable results compared with the measured results in this study. E_{unsat} values used for Unimin Sand under different conditions are summarized in Table 3. The Poisson's ratio υ of soil is equal to 0.334. The coefficient of lateral pressure (K_0) was estimated as 0.42 using empirical relationship (i.e., K_0= 1-sin ϕ'). The interface friction angle (ϕ_i) between the pile and sand was assumed to be ϕ_i =0.7 ϕ'. The dilation angle of Unimin Sand was estimated to be 4.2°, which is slightly higher than 10% of ϕ'. Three different water table levels (i.e., 0 mm, 450 mm, 650 mm deep from soil surface) was considered to achieve varying matric suction profiles. Matric suction was assumed to be linear distributed above water table under hydrostatic conditions (i.e., u_a - $u_w = -\gamma_{water}h_{unsat}$).

Table 3. The Unsaturated Modulus of Elasticity, E_{unsat} for IHT and Sand

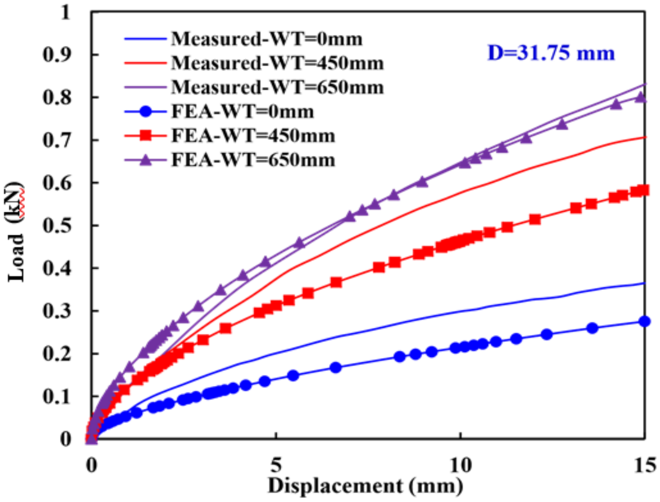
Material	Unimin Sand			IHT (drained condition)				IHT (Undrained condition)			
Water table (m)	0	0.45	0.65	0	2	3	4	0	2	3	4
Eunsat(MPa)	2000	6000	9100	7000	11192	13232	14298	2500	3997	4793	5137

Drained loading condition was assumed for single piles in unsaturated sand. The displacements at the bottom of the model and in the direction perpendicular to the symmetry planes were fixed. The local meshes adjacent to the pile were refined to improve the computational accuracy. A displacement of 15 mm was applied on the top of pile to simulate the loading procedure during model pile tests.

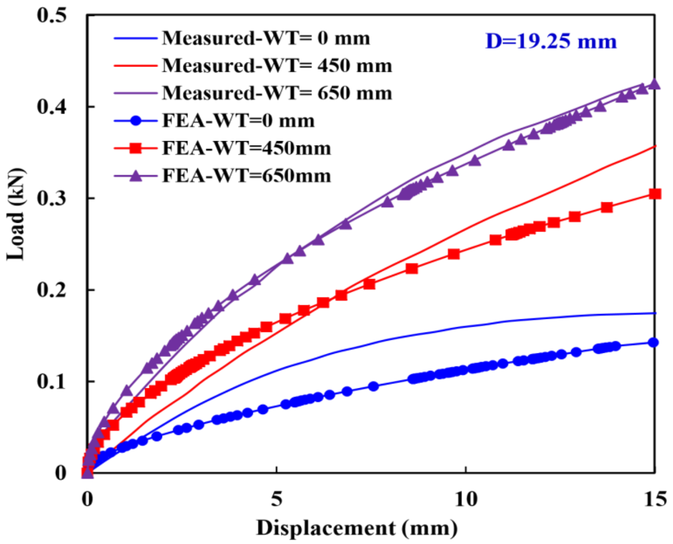
Comparisons between the predicted P – δbehavior of model piles with three different diameters and the measured results obtained from experimental study[10] are shown in Figure 12. The ultimate bearing capacity of single piles at 450 mm water table depth was 2-2.5 times in comparison with saturated conditions (i.e., water table is at ground surface), while the ultimate bearing capacity at 650 mm water table depth were about 5 times higher. The ultimate bearing capacity of single piles increases with an increase in the pile diameter. Acceptable agreement can be observed between the measured and predicted ultimate bearing capacity. These results validate that using modified M-C model to simulate unsaturated soils in FEA can provide reasonable predictions of pile behavior in comparison with the measured results from Vanapalli et al. [10]. However, this numerical technique has some limitations when it is extended for unsaturated sand. The current elastic-perfectly plastic model does not consider the soil dilatancy and strain hardening; due to this reason, it is unable to describe the real behavior of unsaturated sand. More explanation can be found in Al-Khazaali et al. [27].



(a)



(b)

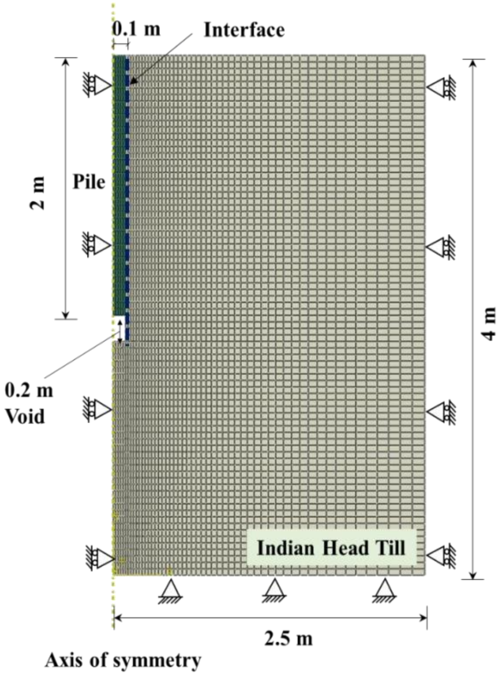


(c)

Fig.12. Comparison between the predicted $P - \delta$ behavior of piles with three diameters using FEA and measured values (a) D =38.3 mm (b) D = 31.75 mm (c) D =19.25 mm

3.4 Pile foundation in unsaturated fine-grained soils

In this study, numerical analysis was performed to investigate the shaft carrying capacity of single piles in an unsaturated fine-grained (UFG) soil (i.e., IHT) under undrained and drained loading conditions. An axialsymmetric model was established using finite element software ABAQUS considering the symmetry of the pile-soil system. The model geometry and meshes are illustrated in Figure 13. The single pile with a diameter of 0.2 m and height of 2 m was modelled as linear-elastic materials. The pile modulus of elasticity E_p =20 GPa and the Possion's ratio, υ= 0.15 was used in the model. The IHT was modelled as an elastic perfectly plastic material with a modified M-C constitutive model extended for unsaturated soils. The procedure of establishing models was similar to the method discussed earlier. The unsaturated modulus of elasticity, $E_{unsat}$was also determined using Eq. 4. The mean value of E_{unsat} along the pile length was used as the uniform soil modulus in the model. E_{unsat} values used for IHT under different conditions are summarized in Table.3. The fitting parameters α =1/10, β =2 was used in this equation. Two values of Poisson's ratio of IHT were used under undrained (i.e., υ_u = 0.49) and drained (i.e., υ_d = 0.37) loading conditions. The coefficient of lateral pressure (K_0) was estimated using empirical relationship (i.e., K_0= 1 - sin ϕ'= 0.61). Four different water table levels (i.e., 0 m, 2 m, 3 m, 4 m) were considered in this model to achieve varying matric suction profiles. The initial suction profile along with depth for different water levels is shown in Figure 14.



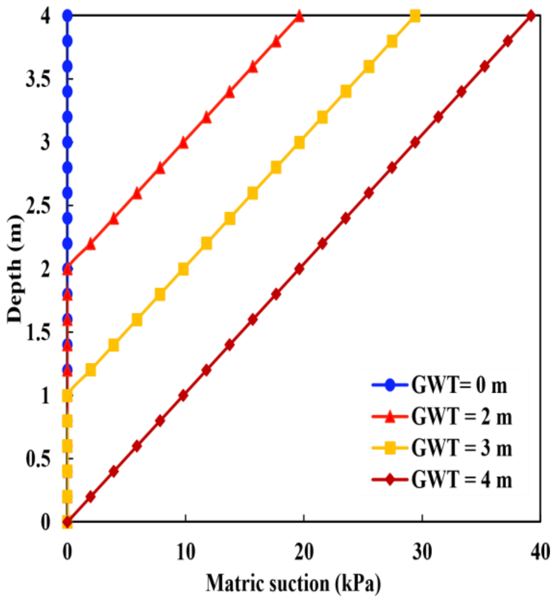
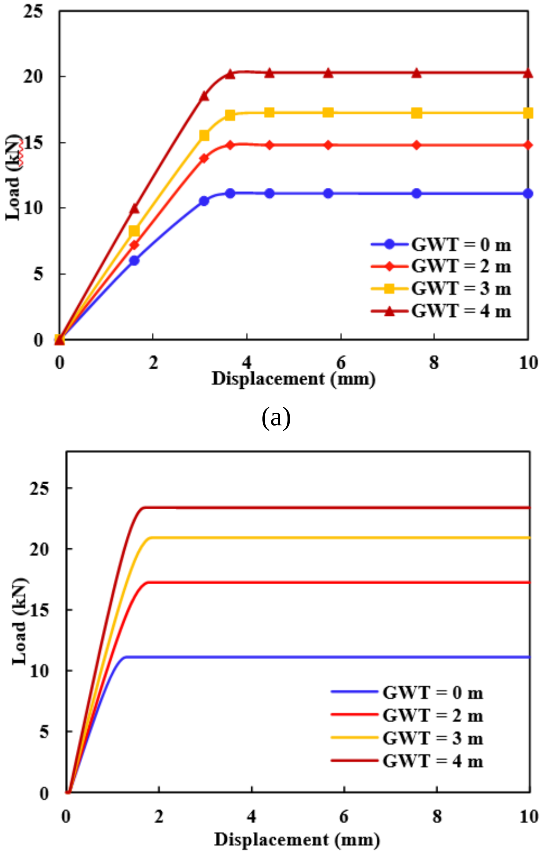


Fig. 13.Details of finite element model**Fig. 14.**Initial linear suction distribution profile . for different ground water tables

The contact cohesive behavior was defined between pile and soil interface in ABAQUS.The contact cohesive behavior is intended for situation that has negligible interface thickness and it assumes a linear elastic tractionseparation law followed by the damage [35]. For drained loading conditions, the shear strength of the interface is defined to be equal to that of IHT based on the results of interface direct shear tests [28]. However, for undrained loading conditions, the shear strength of the interface is usually lower than the undrained shear strength of soil. A reduction parameter α was introduced to estimate undrained interface shear strength. The α value of 0.71 for saturated conditions was used in this model, which was back calculated from pile test results. The αc_u value was estimated as the undrained interface shear strength in the interaction property.

The dilation angle (ψ') of the IHT was assumed to be zero, which was based on two considerations: (i) the dilation of clays, especially for saturated clays or clays with low suction values is negligible compared with coarsegrained soils during shearing; (ii) the increase of ψ' does not influence the linear relationships. ψ' mainly influences $P - \delta$ behavior in the plastic zone instead of elastic zone. More details of the influence of ψ' on the $P - \delta$ behavior is available in Han and Vanapalli [28].

The boundary conditions used in the numerical simulations are shown in Figure 13. The displacements at the bottom of the model and in the direction perpendicular to the symmetry planes were fixed. The local meshes adjacent to the pile were refined for achieving higher computational accuracy. The displacements at the bottom of the model and in the direction perpendicular to the symmetry planes were fixed. A void of 0.2 m was left at the base of pile in order to eliminate the tip resistance, following the procedures used in experimental program (see Companion Paper I for more details). A displacement of 0.01 m was applied vertically on the top of pile to simulate the loading procedure during model pile tests.



(a)

(b)

Fig. 15. Variation of pile shaft carrying capacity at different WT levels for (a) undrained loading conditions (b) drained loading conditions

Figure 15 shows the FEA predictions of pile shaft carrying capacity versus displacement for undrained and drained loading conditions, respectively. The shaft carrying capacity of single piles significantly increases with matric suction increases. The pile shaft capacity under unsaturated conditions were approximately 1.3 to 2 times higher in comparison to saturated conditions. The difference of shaft carrying capacity between saturated and unsaturated conditions is more significant for drained loading conditions in comparison to undrained loading conditions.

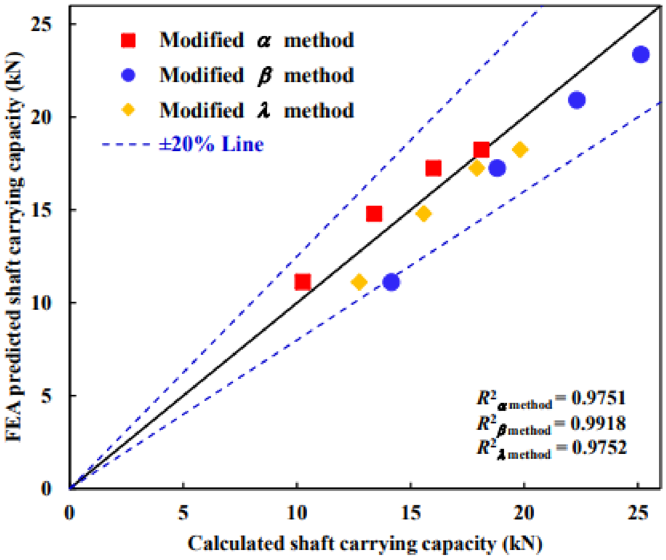


Fig.16. Comparison between calculated pile shaft capacity using modified α, β, λ methods and those predicted from FE models

Vanapalli and Taylan [42] proposed three methods (i.e., modified α, β, λ methods) to predict shaft carrying capacity of single piles in unsaturated soils; which are succinctly summarized in the Companion Paper I. Comparison between calculated pile shaft capacity values using theoretical methods and those predicted from FEA were presented in Figure 16. The coefficient, β = 0.26 was determined for both the saturated and unsaturated soils based on the soilpile interface friction angle. A value of λ= 0.32 is used in this study based on Vanapalli and Taylan [43]. Good agreement can be observed between the calculated values using modified α, β and λ methods and those predicted using FEA with less than 20% deviation. Relatively high Rsquare values are obtained for all three methods. For undrained loading conditions, the FEA predicted results are higher than the calculated results from analytical methods, while for drained loading conditions, the FEA predicted results are conservative in comparison to the calculated results. Varying matric suction values corresponding to apparent cohesion, c_a was realized in the FEA to describe the behavior of unsaturated soils. This numerical technique provides rigorous results for estimating pile shaft carrying capacity in UFG soils.

4 Summary

In this Companion Paper II, numerical techniques were developed using ABAQUS commercial software extending modified M-C model to investigate the influence of matric suction on the behavior of stress versus settlement or load versus displacement (P – δ) behavior, respectively for both shallow and deep foundations. The proposed numerical method takes into account of the nonlinear variation of shear strength and the modulus of elasticity of unsaturated soils, which are he two key properties required. The variations of unsaturated shear strength and elastic modulus with varying matric suction are incorporated into the FE model using a specially written subroutine (USDFLD) along with ABAQUS. The FE model is simple, and it only requires limited number of soil parameters and the soil-water characteristic curve (*SWCC*).

The proposed numerical technique is a valuable tool that provides a rigorous evaluation of the behavior of foundations in unsaturated soils taking account of influence of matric suction. The FE results are also compared with the proposed theoretical approaches and experimental data.Results show that the bearing capacity of the shallow foundation in both coarse-grained and fine-grained soils are significantly influenced by the matric suction. Good agreements have been found between the results derived from the numerical model using ABAQUS and that using the theoretical methods (MESA and MTSA). All the compared results from the two methods are within 20% deviation line with R^2 not less than 95%.

The P – δ behavior of single piles in both unsaturated coarse-grained soils and fine-grained soils were successfully validated extending MESA. The calculated pile shaft carrying capacity using modified α, β and λ methods is consistent with those predicted using FEA with less than 20% deviation. More field investigations are required to validate the theoretical approaches and the numerical modelling results discussed in the Companion Papers I and II. Such studies will encourage the practicing geotechnical engineers to use the proposed theoretical approaches and the numerical methods in the design of foundations in unsaturated soils.

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