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COUPLED GEOTECHNICAL-HYDROLOGICAL DESIGN OF SHALLOW FOUNDATION CONSIDERING SITE SPECIFIC DATA — THEORETICAL FRAMEWORK AND APPLICATION

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ABSTRACT

Occurrence of extreme hydrological events is frequent in recent years. These events impact the performance of many structures specially the foundations which transfer superstructure load to the ground. The shear strength and settlement of soils and foundations are influenced by the degree of saturation of the soil which varies with hydrological parameters such as rainfall, flood, and evapotranspiration. Therefore, the hydrological parameters must be incorporated in the design to obtain the optimum design for a particular location with specific geotechnical parameters. In this paper, a novel procedure, which considers the site specific hydrological parameters into the shallow foundation design, is presented with sample applications in the United States. The degree of saturation of the partially saturated soil within the influence zone of the foundation was modeled using the one-dimensional Richards' equation considering infiltration rate and water table location as the top and bottom boundary conditions, respectively. The historical rainfall data and water table locations for two study areas in Victorville, California and Levelland, Texas were obtained from the U.S. Geological Survey and National Climatic Data Center data repositories. The results from the Victorville site indicated a near 230% increase in the ultimate bearing capacity and a corresponding 80% decrease in the elastic settlement from those calculated assuming the fully saturated condition. On the other hand, there was only a small increase in bearing capacity at the Levelland site with a corresponding decrease in settlement of 40%. These significant differences in results are because of the inherent variation of the soil properties and hydrological parameters for both site locations. The results clearly indicate that shallow foundation design can be improved if the hydrological parameters are incorporated in the design procedure.

Key words: Shallow foundation, hydrological parameters, infiltration, Richards' equation, partially saturated soil.

1. INTRODUCTION

According to the National Climatic Data Center (NCDC), nearly 30 percent of the contiguous U.S. experienced moderate to extreme hydrological events such as heavy rainfall, flood, and drought which ultimately influence the spatial and temporal variation of degree of saturation of the subsurface soil. The effect of degree of saturation of the soil on its mechanical and flow behaviors is well documented in recent years. These two observations clearly show that design of any geotechnical systems must be performed considering the hydrological parameters to accurately quantify their performance.

Shallow foundation, a common type of foundation used to support small to medium size of structures and transfer its loads to the near surface soil, is commonly designed for the worst case geotechnical conditions. That is, the soil is fully saturated with the water table at the ground surface even if the historical water table is well below the influence depth of the shallow foundation and expected to be the same during the lifetime of the structure. Although the foundations are designed to compensate for fully saturated soil conditions, recent case studies indicate that extreme hydrological events such as heavy rainfall, flood, and drought significantly affect settlement behavior of the foundations which may exceed the allowable design value. Thus, the current design approach can be either conservative or unconservative, depending on the type of hydrological event, for locations where the near-surface soil is partially saturated during the design life of the structure (Lu and Likos 2004; Fredlund *et al*. 2012; Briaud 2013). Therefore, the current shallow foundation design must be revised to incorporate the impacts of hydrological events for optimal design (Schnaid *et al*. 1995; Costa *et al*. 2003; Vanapalli and Mohamed 2007; Sheng 2011). Illustrated in Fig. 1 is a shallow foundation with hydrological cycle that changes the degree of saturation of the soil within the influence zone (1.5 × foundation width (B)).

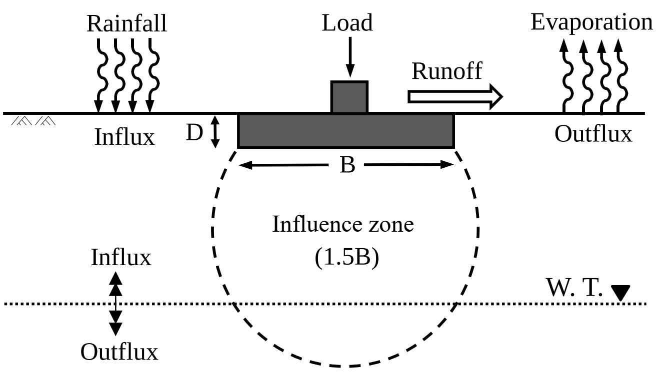

Fig. 1 Hydrological cycle and its influence on the foundation

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A better design procedure will require thorough understanding of the behavior of partially saturated soil and utilization of site specific historical rainfall, evapotranspiration, and water table data. In recent years, a number of efforts have been undertaken to assess the effect of water movement and infiltration on the hydro- mechanical behavior of partially saturated soils. A new framework was developed by Vahedifard *et al*. (2015) to evaluate the influence of steady vertical flow on effective stress-based limit equilibrium analysis of partially saturated slopes. Moreover, Vahedifard and Robinson (2016) proposed a unified method based on model footing and plate load tests to estimate the ultimate bearing capacity of shallow foundation in partially saturated soil considering different surface flux boundary conditions and depth of water table. Furthermore, in the case of shallow foundation design, Vanapalli and Mohamed (2007) proposed a new equation to predict the nonlinear variation of bearing capacity of shallow foundation in partially saturated soils with respect to matric suction and degree of saturation. Oh *et al*. (2009) proposed a method based on model footing tests and load tests to estimate the modulus of elasticity of partially saturated soil considering the soil water characteristic curve (SWCC). Mahmoudabadi and Ravichandran (2017) developed a framework to consider the historical rainfall and water table data for computing the bearing capacity of shallow foundation. Following to that, Ravichandran *et al*. (2017) applied the probabilistic analysis in design process of shallow foundation with respect of hydrological parameters.

Since all the above mentioned methods addressed various pieces of shallow foundations design, the objectives of this study are to develop a procedure for coupling site specific hydrological parameters with geotechnical parameters for the design of shallow foundation and to demonstrate the procedure through sample applications. To this end, the numerical solution of the Richards' equation was considered to capture the variation of the degree of saturation and matric suction beneath the ground surface considering the historical rainfall and water table data as top and bottom boundary conditions, respectively. Finally, Monte Carlo simulations were used to compute the bearing capacity and elastic settlement of a shallow foundation in partially saturated soil for the study areas.

2. A FRAMEWORK FOR COUPLING GEOTECHNICAL AND HYDROLOGICAL DATA IN DESIGN PROCESS

The key steps for incorporating the hydrological parameters into the conventional shallow foundation design are: (1) develop a mathematical model for computing spatial and temporal variation in the degree of saturation and matric suction, (2) implement the mathematical model and solve it considering resultant infiltration and water table as the top and bottom boundary conditions, respectively, (3) compute average matric suction and degree of saturation of soil within the influence zone of the foundation, and (4) compute ultimate bearing capacity and settlement using equations that consider the effects of matric suction and degree of saturation. The details of these key steps are presented below.

2.1 Mathematical Model for Flow in Soil and Boundary Conditions

The one dimensional vertical movement of water through partially saturated soil was represented by the Richards' equation (Richards 1931) which is shown in Eq. (1). This nonlinear partial differential equation derived from Darcy's law, predicts a decrease of the soil-water diffusivity for the different flux rates as infiltration progress.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K\left(1+\frac{\partial \psi}{\partial z}\right)\right] \tag{1}$$

where t is the time, z is the depth from the ground surface, θ is the volumetric water content, K is the unsaturated hydraulic conductivity, and $\partial\psi / \partial z$ is the hydraulic gradient. Although the problem considered in this study is three-dimensional in nature, it is assumed that the one-dimensional model is reasonably accurate to predict the vertical movement of the water. Since the pressure head, ψ, is considered as the primary variable to be determined in this study, the two other variables in the Richards' equation, θ and K, are required to be expressed as functions of ψ. The hydraulic conductivity of partially saturated soil, K, is expressed as $K = K_{sat} \times K_r$, where K_{sat} is the hydraulic conductivity of the soil under fully saturated condition and K_r is the relative hydraulic conductivity of the soil under partially saturated condition. In this study, both θ and K_r are expressed as functions of ψ using a soil water characteristic curve (SWCC). Among the many SWCCs and corresponding relative hydraulic conductivity functions, the equations proposed by van Genuchten (1980) were used in this study. The van Genuchten model has three advantages: (1) there are no discontinuities in the SWCC functions, (2) it is reasonably accurate, and (3) it can be easily used by practice engineers. The equations of SWCC and corresponding K_r functions are given in Eqs. (2) and (3), respectively,

$$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1+(\alpha\psi)^n\right]^m} \tag{2}$$

$$K_r(\psi) = \frac{\left\{1-(\alpha\psi)^{n-1}\left[1+(\alpha\psi)^n\right]^{-m}\right\}^2}{\left[1+(\alpha\psi)^n\right]^{m/2}} \tag{3}$$

where α is inversely proportional to the air entry value of the soil, and n is a fitting parameter, $m = 1 - 1/n$, θ_s is saturated water content, and θ_r is residual water content.

The Richards' equation has been solved considering various numerical solution approaches (van Genuchten 1982; Feddes *et al*. 1988; Celia *et al*. 1990; Warrick 1991; Zaidel and Russo 1992; Baker 1995; Pan *et al*. 1996; Romano *et al*. 1998; van Dam *et al*. 2000). In this study, the Finite Volume Method (FVM) was used to solve the Richards' equation for initial and boundary conditions. The details of the numerical solution are described in Eqs. (4) to (10). Figure 2 displays a general model for the discretization of a portion of soil containing three nodes.

In order to solve the Richards' equation, first the equation needs to be written in term of the pressure head for one dimensional vertical infiltration. Thus, $\partial\theta / \partial t$ is expressed as $\partial\theta / \partial\psi \times \partial\psi / \partial t = C\, \partial\psi / \partial t$ and substituted in Eq. (1).

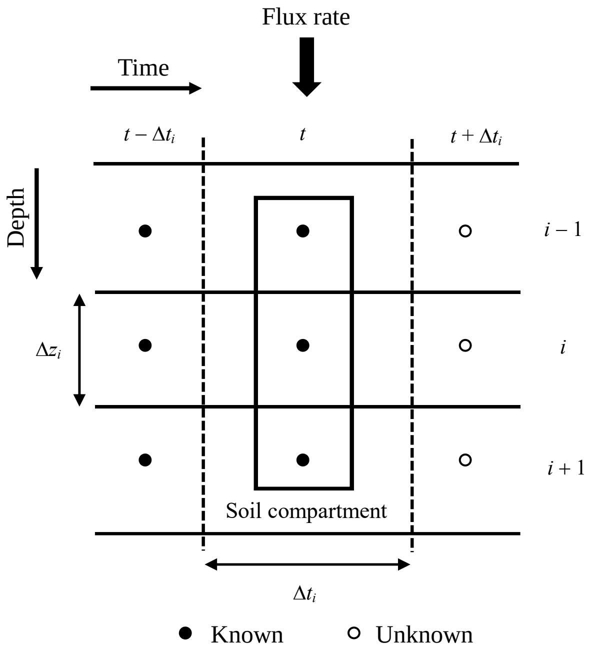

Fig. 2 Discretization of a portion of soil for numerical iteration of unsaturated flow

$$C\frac{\partial\psi}{\partial t}-\frac{\partial}{\partial z}\left(K\frac{\partial\psi}{\partial z}+K\right)=0 \tag{4}$$

where C is the specific moisture capacity ($\partial\theta / \partial\psi$). Then, the Eq. (4) is integrated with respect to the time (t) and depth (z) as follow.

$$\int_{i-1/2}^{i+1/2}\int_{t}^{t+\Delta t} C\frac{\partial\psi}{\partial t}dtdz-\int_{t}^{t+\Delta t}\int_{i-1/2}^{i+1/2}\frac{\partial}{\partial z}\left(K\frac{\partial\psi}{\partial z}+K\right)dzdt=0 \tag{5}$$

The left hand side of the integration is rewritten in a discretized form, which is expressed in Eq. (6).

$$\int_{i-1/2}^{i+1/2}\int_{t}^{t+\Delta t} C\frac{\partial\psi}{\partial t}\,dtdz=\int_{i-1/2}^{i+1/2} C(\psi^{t+\Delta t}-\psi^{t})\,dz=C_i^{t+\Delta t}(\psi_i^{t+\Delta t}-\psi_i^{t})\,\Delta z \tag{6}$$

The right hand side is first solved for spatial variation, as shown in Eq. (7), and then, the integration is discretized into the temporal form, as shown in Eq. (8).

$$\begin{aligned}&\int_{t}^{t+\Delta t}\int_{i-1/2}^{i+1/2}\frac{\partial}{\partial z}\left(K\frac{\partial\psi}{\partial z}+K\right)dzdt\\&=\int_{t}^{t+\Delta t}\left[\left(K\frac{\partial\psi}{\partial z}+K\right)_{i+1/2}-\left(K\frac{\partial\psi}{\partial z}+K\right)_{i-1/2}\right]dt\end{aligned} \tag{7}$$

$$\begin{aligned}&C_i^{t+\Delta t}(\psi_i^{t+\Delta t}-\psi_i^{t})\Delta z=\\&\left[\left(K_{i+1/2}^{t+\Delta t}\frac{\psi_{i+1}^{t+\Delta t}-\psi_i^{t+\Delta t}}{\Delta z}+K_{i+1/2}^{t+\Delta t}\right)\right.\\&\left.-\left(K_{i-1/2}^{t+\Delta t}\frac{\psi_{i}^{t+\Delta t}-\psi_{i-1}^{t+\Delta t}}{\Delta z}+K_{i-1/2}^{t+\Delta t}\right)\right]\Delta t\end{aligned} \tag{8}$$

Considering m as the iteration level and pressure head at iteration $m + 1$ as the unknown value, the complete spatial and temporal form of the Richards' equation is expressed in Eq. (9).

$$\begin{aligned}&C_i^{t+\Delta t,m}(\psi_i^{t+\Delta t,m+1}-\psi_i^{t})\,\Delta z\\&=\left[\left(K_{i+1/2}^{t+\Delta t}\frac{\psi_{i+1}^{t+\Delta t,m+1}-\psi_i^{t+\Delta t,m+1}}{\Delta z}+K_{i+1/2}^{t+\Delta t}\right)\right.\\&\left.-\left(K_{i-1/2}^{t+\Delta t}\frac{\psi_{i}^{t+\Delta t,m+1}-\psi_{i-1}^{t+\Delta t,m+1}}{\Delta z}+K_{i-1/2}^{t+\Delta t}\right)\right]\Delta t\end{aligned} \tag{9}$$

Finally dividing the Eq. (9) by Δz and rearranging the formulation, the final form of the Richards' equation is written as follow (Eq. (10)).

$$\begin{aligned}&C_i^{t+\Delta t,m}(\psi_i^{t+\Delta t,m+1}-\psi_i^{t})\\&=\left[\left(K_{i+1/2}^{t+\Delta t}\frac{\psi_{i+1}^{t+\Delta t,m+1}-\psi_i^{t+\Delta t,m+1}}{(\Delta z)^2}-K_{i-1/2}^{t+\Delta t}\frac{\psi_{i}^{t+\Delta t,m+1}-\psi_{i-1}^{t+\Delta t,m+1}}{(\Delta z)^2}\right)\right.\\&\left.+\left(\frac{K_{i+1/2}^{t+\Delta t}-K_{i-1/2}^{t+\Delta t}}{\Delta z}\right)\right]\Delta t\end{aligned} \tag{10}$$

Since the obtained numerical solution of the Richards' equation is a time consuming process, a MATLAB code was developed to solve the Eq. (10) and implemented on the Clemson University's supercomputer, the Palmetto Cluster, to perform the simulation in reasonable runtimes. The variation in both hydraulic head and water content, as explained above, could then be solved in terms of the ultimate bearing capacity and elastic settlement for the partially saturated soil. It is worth to mention that the proposed solution approach considers the capillary action while solving the Richards' equation.

2.2 Boundary and Initial Conditions

The one-dimensional water infiltration into the soil profile with a specific water table is shown in Fig. 3 for purposes of illustrating the problem and the boundary conditions. The top and bottom boundary condition are displayed and located on the ground surface and the water table level, respectively, as presented in Fig. 1.

In this study, both pressure head and flux boundary conditions were applied at the top boundary depending upon the magnitude of the rainfall and the specific moisture capacity. In case of ponding, when the infiltration rate is greater than the saturated hydraulic conductivity, the pressure head type boundary condition ($\theta_{up} = \theta_0$) is applied. When all water infiltrates into the soil, the flux type boundary condition ($q_{up} = q_0$) is applied, which is computed using the actual rainfall data. In addition, the soil was assumed to be dry at the beginning of each simulation. Since the water table location and resultant infiltration vary with climatic conditions for each specific location, appropriate values must be determined in a probabilistic manner considering historical rainfall, evapotranspiration, and water table data.

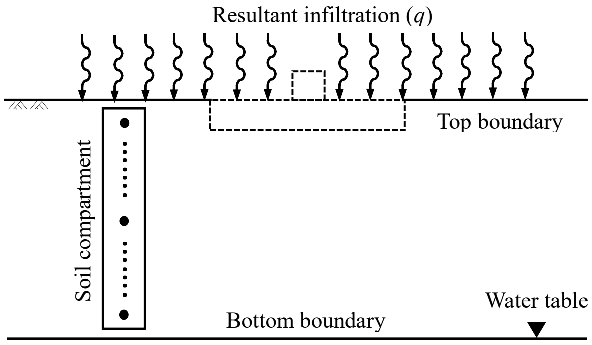

Fig. 3 Partially saturated zone of a soil profile with vertical infiltration

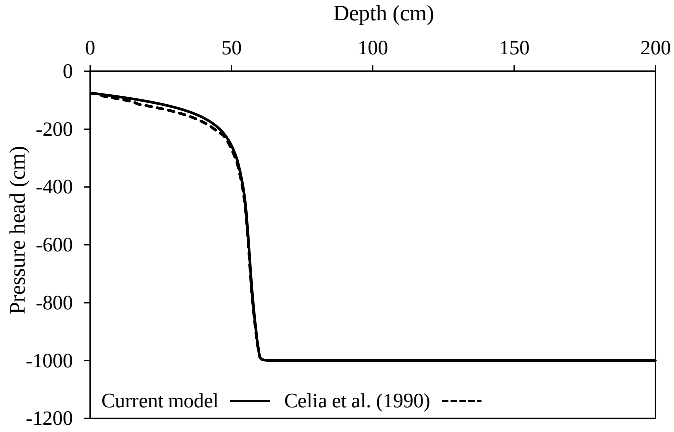

Fig. 4 Numerical solution scheme verification for the Richards' equation

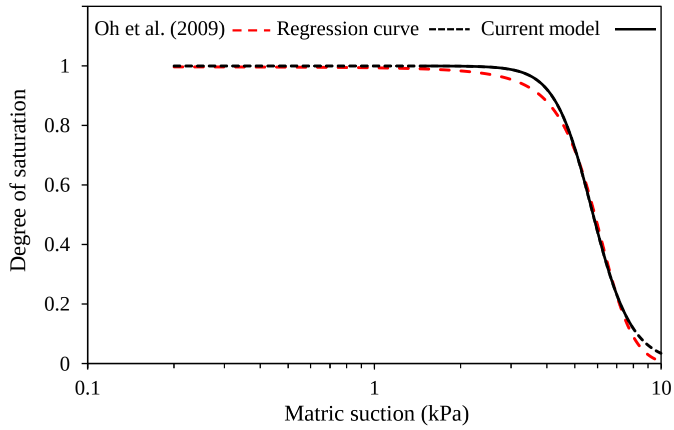

Fig. 5 Soil water characteristics curve (SWCC) verification for infiltration process

2.3 Model Verification

The presented framework includes two primary algorithms, the Richards' equation and SWCC, which together are able to sort out the coupled geotechnical-hydrological problem. Hence, the validity of the model should be tested through a comparison of the results of the numerical Richards' equation and SWCC. In order to accomplish that, a generalized solution developed by Celia *et al*. (1990) was used to validate the water infiltration process of the proposed approach (Fig. 4). In addition, the SWCC results of Oh *et al*. (2009) were compared with the output of the current model to check the accuracy of the van Genuchten SWCC model in this study (Fig. 5). All constants, which are used to validate the proposed model, are listed in Tables 1 and 2.

3. FOUNDATION DESIGN IN PARTIALLY SATURATED SOIL

3.1 Bearing Capacity Criteria

The contribution of matric suction and degree of saturation towards the bearing capacity of partially saturated soils has been the subject of fairly extensive study (Steensen-Bach *et al*. 1987; Costa *et al*. 2003; Mohamed and Vanapalli 2006; Vanapalli and Mohamed 2007; Oh and Vanapalli 2009; Oh and Vanapalli 2013). Among the many available equations, the ultimate bearing capacity equation proposed by Vanapalli and Mohamed (2007) was used in this study to predict the nonlinear variation of bearing capacity in partially unsaturated soils with respect to the matric suction for shallow foundation (Eq. (11)).

$$q_u = \Big[c' + (u_a - u_w)_b (\tan\phi' - S^{\psi_a} \tan\phi') + (u_a - u_w)_{avg} S^{\psi_a} \tan\phi' \Big] N_c F_{cs} F_{cd} + \gamma D_f N_q F_{qs} F_{qd} + 0.5\, \gamma B N_\gamma F_{\gamma s} F_{\gamma d} \tag{11}$$

where c' is the cohesion of soil, γ is the unit weight of the soil, D_f is the depth of foundation, B is the width of foundation, N_c, N_q and N_γ are the non-dimensional bearing capacity factors that are functions of the soil friction angle ϕ', F_{-s} and F_{-d} are the shape and depth factors, respectively, $(u_a - u_w)_b$ is the air entry value which is computed from the SWCC, $(u_a - u_w)_{avg}$ is the average matric suction within the foundation influence zone, S is the degree of saturation, and ψ_a is the shear strength fitting parameter which is expressed in Eq. (12).

Table 1 Infiltration parameters for the constant head pressure model (Celia *et al*. 1990)

Parameters	α	θ_s	θ_r	n	m	K_{sat} (cm/s)	H_{top} (cm)	H_{bottom} (cm)	T (day)	Δt (s)
Values	0.0335	0.368	0.102	2	0.5	0.00922	–75	–1000	1	144

Table2 Estimated SWCC parameters for the Oh *et al*. (2009) model

Parameters	α	θ_s	θ_r	n	m	K_{sat} (cm/s)
Values	1.75	1.00	0.00	6.80	0.85	1.00

$$\psi_a = 1.0 + 0.34(I_p) - 0.0031(I_p)^2 \tag{12}$$

where I_p is the plasticity index of the soil. The average matric suction in the above bearing capacity equation is calculated using the Eq. (13),

$$(u_a - u_w)_{avg} = \frac{\sum_{i=1}^{p} \big[(u_a - u_w)_i \big]}{p} = \frac{\sum_{i=1}^{p} [-\psi_i\, \gamma_w]}{p} = -\psi_{avg} \gamma_w \tag{13}$$

where $(u_a - u_w)_i$ is the matric suction at the i^{th} node of soil within the influence zone; p is the last soil node within the influence zone; ψ_i is the pressure head at the i^{th} node of soil within the influence zone, ψ_{avg} is the average pressure head within the foundation influence zone and γ_w is the unit weight of water. The average matric suction and degree of saturation are key variables, which affect the ultimate bearing capacity of the soil within the influence zone of foundation and were calculated using the procedure described above.

3.2 Settlement Criteria

The elastic settlement of the foundation was calculated using the simplified equation shown in Eq. (14) (Bowles 1987),

$$S_e = q_0(\alpha B')\frac{1-\mu_s^2}{E} I_s I_f \tag{14}$$

where S_e is the elastic settlement of the foundation, q_o is the net pressure at the bottom of the foundation due to applied structural load, α is a non-dimensional parameter that depends on the point at which settlement is calculated for a flexible foundation, B' is the effective dimension of the foundation, μ_s is the Poisson's ratio, I_s and I_f are factors associated with shape and depth of the foundation, respectively, and E is the average elastic modulus of the soil within the influence zone. Of all these parameters, E is the only parameter which is affected by the degree of saturation and matric suction of the soil within the influence zone. Since the degree of saturation and the matric suction are computed following the procedure described before, the elastic settlement can be computed if E is expressed as a function of degree of saturation and matric suction.

Various empirical equations have been proposed to predict the elastic modulus of soil as a function of matric suction and degree of saturation (Steensen-Bach *et al*. 1987; Schnaid *et al*. 1995; Costa *et al*. 2003; Rojas *et al*. 2007; Oh *et al*. 2009; Vanapalli and Oh 2010; Vanapalli and Adem 2013). In this study, the equation proposed by Oh *et al*. (2009), shown in Eq. (15), was used to estimate the modulus of elasticity in partially saturated coarse-grained soils.

$$E_{unsat} = E_{sat}\left[1+\alpha\frac{u_a-u_w}{P_a/101.3}S^{\beta}\right] \tag{15}$$

where E_{sat} is the modulus of elasticity under saturated condition, S is the degree of saturation, $(u_a - u_w)$ is the matric suction, α and β are fitting parameters, and P_a is the atmospheric pressure. For coarse- and fine-grained soils, the recommended fitting parameter, β, is equal to 1 and 2, respectively. Also, the fitting parameter, α, depending upon the plasticity index (I_p) can be computed using the following empirical equation (Eq. (16)), developed by Oh *et al*. (2009).

$$1/\alpha = 0.5 + 0.312(I_p) + 0.109(I_p)^2 \quad (0 \le I_p(\%) \le 12) \tag{16}$$

It should be noted that to calculate the total settlement of shallow foundation, the consolidation settlement is also required. The consolidation settlement is omitted in this study for two reasons. The first reason is that the consolidation settlement is a long term process which usually takes years to show significant settlement especially when the foundation is supported by fine-grained soil. However, in reality, the degree of saturation of the soil within the influence zone fluctuates with the rainfall intensity and duration and other factors. In this study, a 3-day rainfall is considered which is a short duration compared to the time it takes to show significant consolidation. In such situation, accurately computing the change in consolidation settlement due to the change in degree of saturation is a difficult task. That is why we only considered the immediate settlement (elastic settlement) in our study. One could compute the consolidation settlement considering traditional consolidation parameters and add it with the elastic settlement for the shake of completeness.

The second reason is the lack of well-established correlations for computing the consolidation parameters such as compression index, recompression index, and preconsolidation pressure as functions of degree of saturation and/or matric suction. When such correlations are available, one could calculate the additional consolidation settlement due to the variation in degree of saturation and add it with that of primary consolidation settlement based on saturated parameters. The framework presented in this paper is flexible enough to incorporate additional events and make accurate predictions in the future.

4. APPLICATION OF PROPOSED METHOD TO STUDY AREAS

The flowchart of the procedure employed in this study is presented in Fig. 6. The application of the proposed procedure requires the computation of average matric suction and degree of saturation within the influence zone of shallow foundation using the site specific historical rainfall and water table records. These two random variables are considered as the boundary conditions which change with return periods as will be discussed in more detail in the rainfall and water table distribution section. Thus, the primary variables can be best estimated using probabilistic methods. In order to perform the probabilistic analysis, first the distributions of historical rainfall and water table were used to generate random input variables which were used as boundary conditions. Then, Monte Carlo simulation technique was used to generate 10,000 random input variables in this study to compute the bearing capacity and elastic settlement of a shallow foundation in partially saturated soil. It should be noted that the inherent randomness of soil properties can also be incorporated into the analysis, but to allow for comparisons between the saturated and partially saturated conditions, the geotechnical parameters such as shear strength parameters are kept constant during the simulations. However, the unit weight of the soil changes with varying degrees of saturation computed within the influence zone after each simulation.

4.1 Studied Site Locations

Two sites were selected in this study to show the variation of the ultimate bearing capacity and elastic settlement with matric suction (or degree of saturation). The first case study site was located in Victorville, California. Victorville was selected due to its arid climate and the availability of van Genuchten SWCC parameters for the Adelanto Loam soil type found in this region. The SWCC parameters of the Adelanto Loam (SM) were taken from the report by Zhang (2010). The soil strength parameters of the site were obtained from a geotechnical report by Kleinfelder (Chowdhury 2006). Levelland, Texas, was selected as the second site studied in this paper. The soil strength parameters were obtained from a geotechnical report provided by Amarillo Testing and Engineering, Inc. (Gonzalez 2009). Despite the availability of soil parameters for this region, the van Genuchten parameters did not exist. Therefore, the van Genuchten parameters for Levelland were obtained from the class average value of hydraulic parameters for the twelve USDA textural classes from the program Rosetta (Schaap 2000). The soil classification criteria in the geotechnical report was then used to determine which class was best suited for the Levelland soil, and was considered to be in the sandy-clay (SC-SM) textural class. The plan view and selected van Genuchten SWCC parameters for these two sites are presented in Fig. 7 and Table 3, respectively.

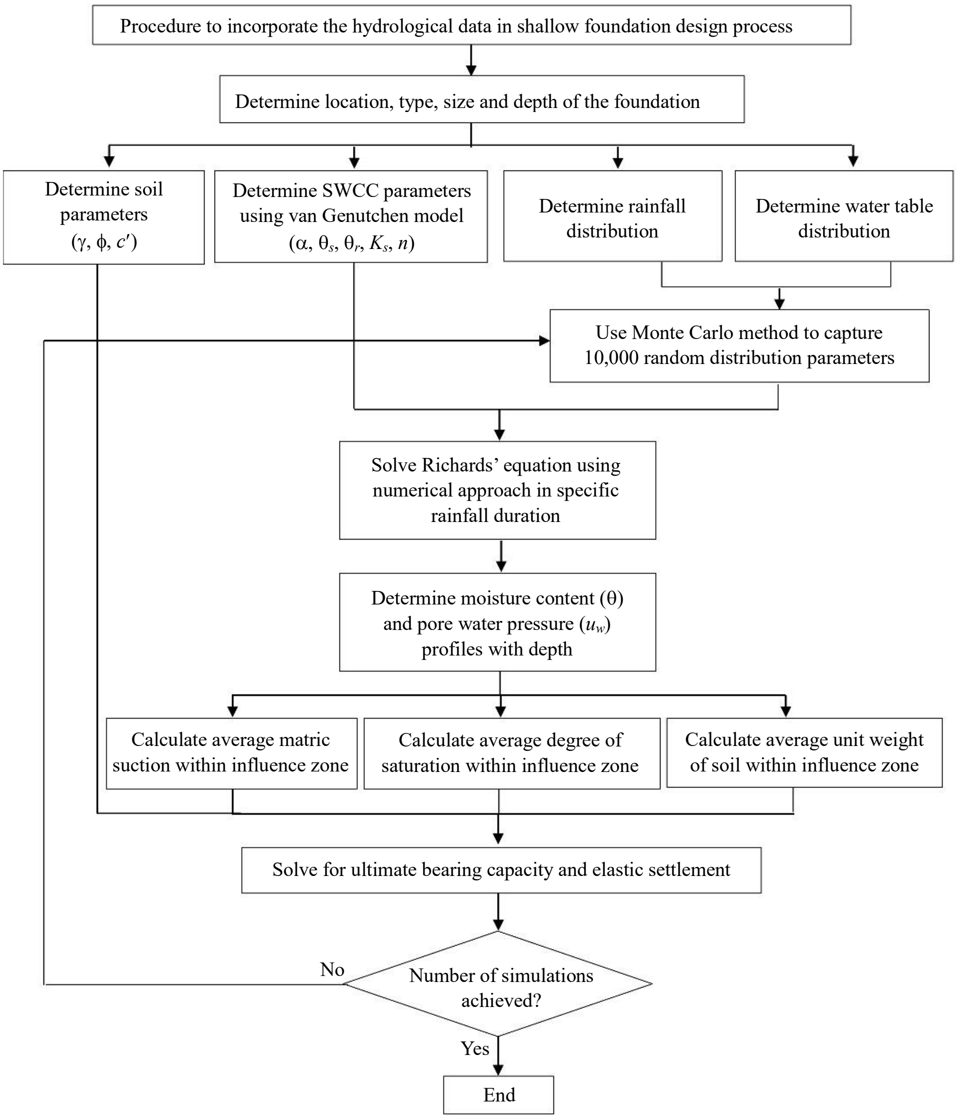

Fig. 6 Simulation flowchart to incorporate the hydrological data into shallow foundation design

Fig. 7 Plan view location of (left) Victorville, CA, and (right) Levelland, TX

Table 3 SWCC and soil strength parameters for Victorville, CA, and Levelland, TX, sites

SWCC & soil strength parameters \ Locations	Victorville, CA	Levelland, TX
Saturated volumetric water content, θ_s	0.423	0.430
Irreducible volumetric water content, θ_r	0.158	0.007
Model parameter, α (m^{-1})	0.321	1.32
Model parameter, n	2.11	1.51
Hydraulic conductivity, k_s (cm/hr)	0.21	0.11
Dry unit weight, γ_d (kN/m^3)	16.20	18.56
Void ratio, e	0.605	0.401
Friction angle, ϕ' (deg.)	33	31
Cohesion, c' (kPa)	0	0
Air entry value, $(u_a - u_w)_b$ (kPa)	14	1.5
Plasticity index (I_p)	5	8

4.2 Rainfall and Water Table Distributions

The rainfall data for Victorville, CA, and Levelland, TX, were obtained from the National Climatic Data Center (NCDC) which record daily rainfall values. In this study, the annual maximum series were used and constructed by extracting the highest precipitation for a particular return period in each successive year. The maximum annual rainfall has been tabulated in millimeter for a return period of 76 years for both study sites. The depth of the water table is another factor which affects the matric suction and degree of saturation of a partially saturated soil within the foundation influence zone. The required data was taken from the U.S. Geological Survey (USGS) and for the same return period which was assumed for rainfall data. To determine the best fitting distribution for the annual maximum rainfall and water table data, the probability paper plotting technique was used. Type I extreme largest (Gumbel distribution), the Type II extreme largest (Frechet distribution), and the Type III extreme largest (Weibull distribution) were checked for the best fit, and the Gumbel distribution was deemed the best regression based on R-squared (R^2) values. The Gumbel probability paper distribution parameters, mode (μ_n) and standard deviation (β_n), can be determined using Eq. (17),

$$-\ln\left(-\ln\left(\frac{i}{n+1}\right)\right) = \frac{(x_i - \mu_n)}{\beta_n} \tag{17}$$

where x_i is the annual maximum historical rainfall or water table data and n is the number of data points. The probability plots of the rainfall and water table data based on the Gumbel distribution is shown in Figs. 8 and 9, respectively, for both study sites.

The average degree of saturation and matric suction within the influence zone were computed by applying the rainfall intensity and water table location predicted by Eq. (17) for 10,000 random cases using Monte Carlo method. The duration of the rainfall was assumed to be three days to simulate the heavy rainfall condition.

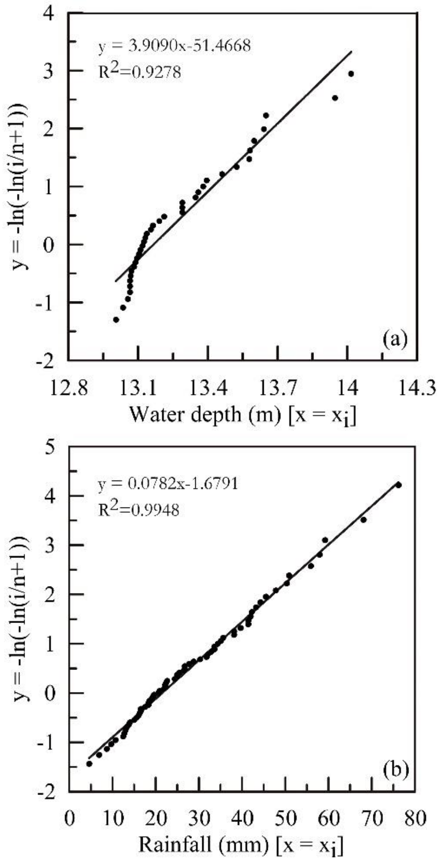

Fig. 8 Type I extreme largest (Gumbel distribution) for water depth and rainfall data for Victorville, CA

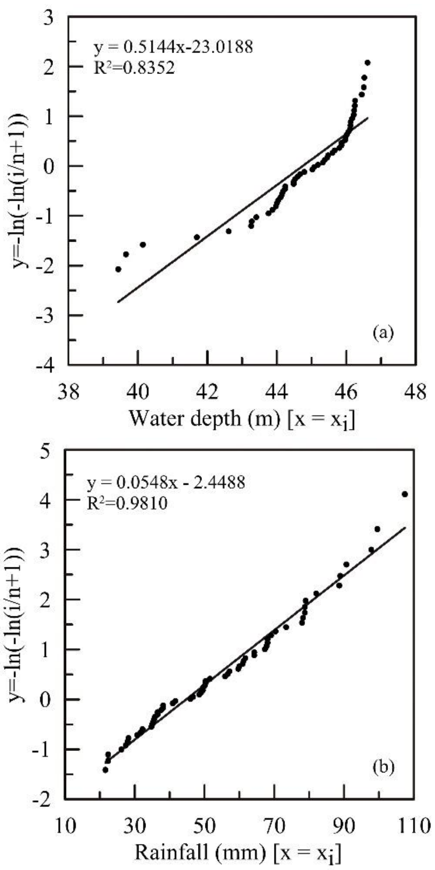

Fig. 9 Type I extreme largest (Gumbel distribution) for water depth and rainfall data for Levelland, TX

4.2 Resultant Infiltration-Top Boundary Condition

The resultant infiltration can be computed from rainfall intensity, surface runoff, and evapotranspiration value for each site. Since three days of continuous rainfall was assumed in this study to simulate a heavy rainfall condition in shallow foundation design, the effect of surface runoff and the evapotranspiration were ignored. However, runoff can be taken into account in the proposed procedure by quantifying its value and subtracting that from the total rainfall intensity. Also using a similar manner, the evapotranspiration can be easily computed based on the Hamon (1961) method in terms of potential evapotranspiration (PET) and can be subtracted from rainfall intensity as well.

4.3 Structural Load and Foundation Size

Square foundations with width, B = 1.0, 1.5, and 2.0 m located at depths, D = 0.5, 0.75, and 1.0 m were used in this study to investigate the infiltration effect for different foundation influence zones. A uniform load of 200 kN/m^2 was applied to all the cases studied.

5. RESULTS AND DISCUSSION

After analyzing 10,000 simulations, the average variation of matric suction for various degree of saturation are captured and demonstrated in Fig. 10 for both site locations. It can be seen in Fig. 10 that the infiltration process is much faster in the Victorville site than in the Levelland region. This is because of the inherent differences in the soil properties for these two locations, which have already been discussed. After three days of continuous rainfall, the degree of saturation in Victorville ranges between 55% and 84%, while this range is between 25% and 35% for Levelland. This huge difference is caused by the existence of the fine-grained soil in the Levelland region which decreases the soil porosity and makes the soil less permeable. Since the water does not infiltrate deep enough into the soil at Levelland, the degree of saturation profile varies only within a small depth. This leads to an insignificant suction variation for this site.

Changing the matric suction and degree of saturation affect the soil shear modulus which directly influences the elastic settlement of the shallow foundation. In general, increasing the matric suction (or decreasing the degree of saturation) has a considerable impact on reducing the foundation settlement. As is shown in Figs. 11 and 12, the computed elastic settlement of various shallow foundations depicts a discrepancy for the Victorville and Levelland areas in terms of degree of saturation and matric suction. Based on the results, the elastic settlement of the foundation in Levelland, TX, is greater than in Victorville, CA. For both locations, the width of the foundation has a greater impact on the settlement rather in comparison to the depth. In the Victorville region, each of the studied cases has a minimum settlement which occurs within a range of 68% to 75% degree of saturation. As the results show, it seems that increasing the matric suction leads to a narrow range of settlement for the foundations with the same width except for the width equal to 1.0 m in which the influence zone is smaller than others and the entire zone is influenced by the infiltrated water. For the Levelland region, the elastic settlement for all different foundation sizes decreases by slightly increasing in the degree of

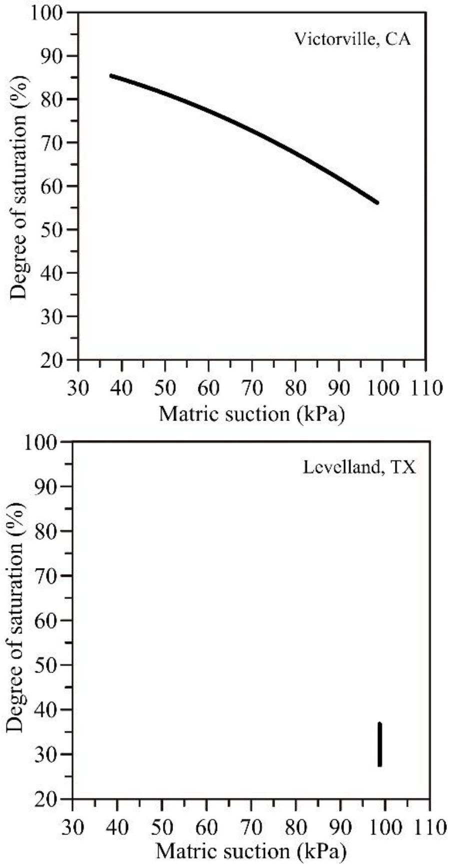

Fig. 10 Average variation of matric suction with different degrees of saturation considering all various studied cases

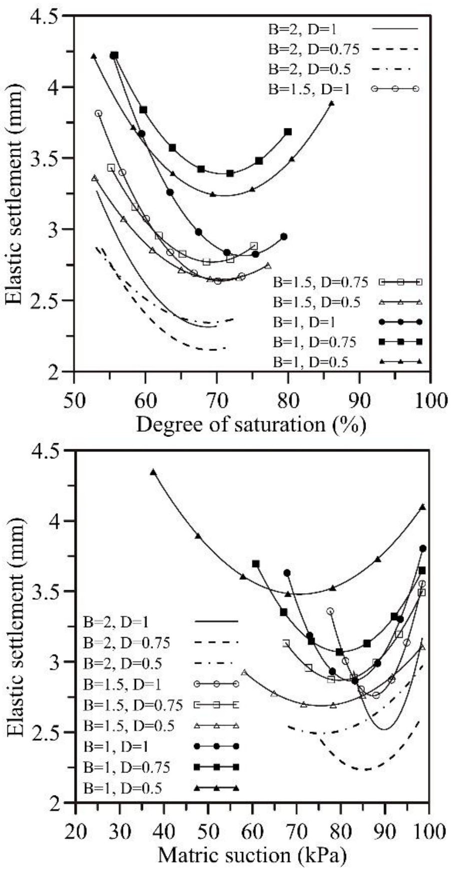

Fig. 11 Elastic settlement of Victorville, CA, site location after 3-day continuous rainfall

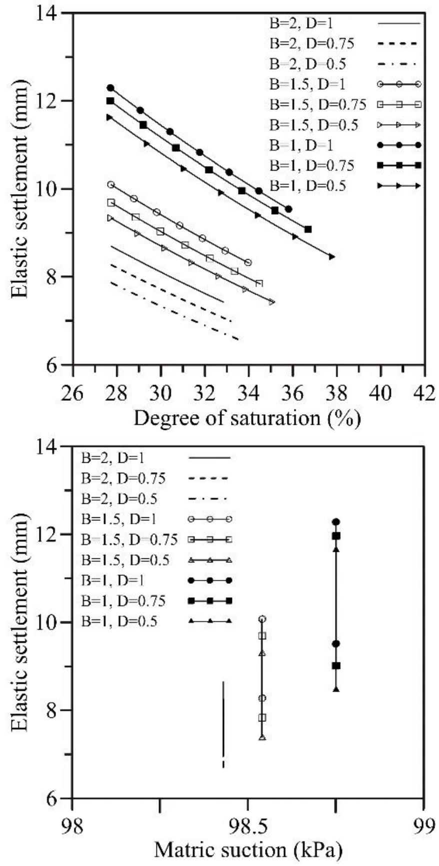

Fig. 12 Elastic settlement of Levelland, TX, site location after 3-day continuous rainfall

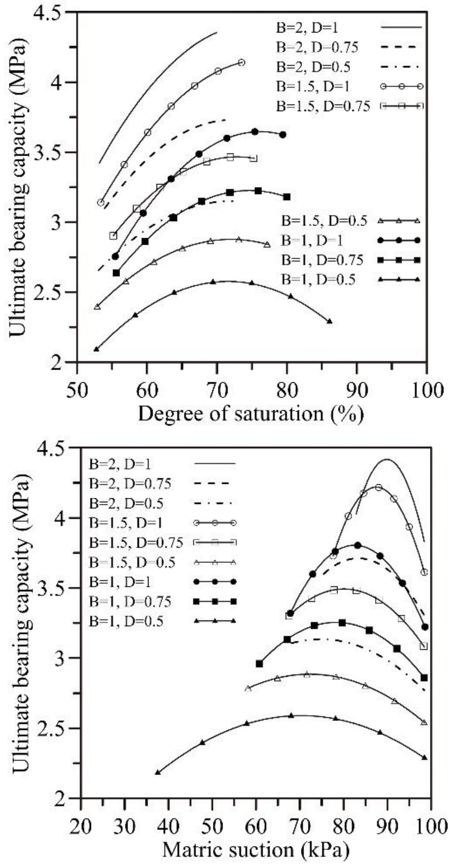

Fig. 13 Ultimate bearing capacity of Victorville, CA, site location after 3-day continuous rainfall

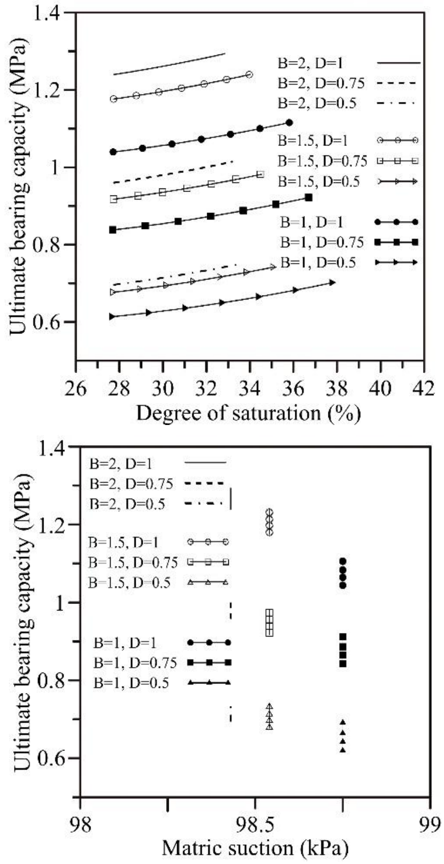

Fig. 14 Ultimate bearing capacity of Levelland, TX, site location after 3-day continuous rainfall

saturation so that the higher settlement values occur within the lower values of the degree of saturation. Also, it can be seen in Fig. 12 that the elastic settlement decreases for a small variation of matric suction for each foundation size. This was happened due to increase in soil modulus of elasticity which is depend on both soil degree of saturation and corresponding matric suction within the foundation influence zone. Since the degree of saturation can significantly change even for the condition that the matric suction shows a very small variation, these changes ultimately alter the soil stiffness and elastic settlement.

In terms of the ultimate bearing capacity, the calculated values show a similar pattern for each foundation case due to the degree of saturation and matric suction for the Victorville region (Fig. 13) in which the depth factor governs the design parameter. In Levelland, the ultimate bearing capacity increases consistently with increasing degree of saturation for all the cases considered in this study (Fig. 14). The ultimate bearing capacity in Victorville also has maximum values that have occurred within a range of 70% to 80% degree of saturation and 70 to 90 kPa matric suction.

In order to assess the contribution of the matric suction in foundation design criteria, a comparison between the presented method and the routine design procedure, in which the soil is assumed fully saturated, is required here. Therefore, the elastic settlement and ultimate bearing capacity of each shallow footing was computed using Bowles' and Meyerhof's (Bowles 1987; Meyerhof 1963) general equations, respectively (Table 4).

Table 4 Ultimate bearing capacity and settlement for two different site locations considering fully saturated condition (routine design procedure)

Width, B (m)	Depth, D (m)	Victorville, CA		Levelland, TX	
		Ultimate bearing capacity (kPa)	Elastic settlement (mm)	Ultimate bearing capacity (kPa)	Elastic settlement (mm)
2.00	1.00	1501.90	20.45	1218.40	14.16
2.00	0.75	1131.33	19.93	915.85	13.79
2.00	0.50	921.69	19.30	741.49	13.36
1.50	1.00	1426.26	24.07	1162.29	16.66
1.50	0.75	1087.79	23.61	883.76	16.34
1.50	0.50	878.01	23.06	708.25	15.96
1.00	1.00	1303.66	29.73	1071.41	20.58
1.00	0.75	987.06	29.39	807.82	20.35
1.00	0.50	840.19	28.97	680.19	20.05

Table 5 Comparison of shallow foundations design parameters considering proposed method and fully saturated condition (routine design procedure)

Width, B (m)	Depth, D (m)	Victorville, CA Difference (%)		Levelland, TX Difference (%)	
		Ultimate bearing capacity	Elastic settlement	Ultimate bearing capacity	Elastic settlement
2.00	1.00	+194.0	−84.0	+6.20	−38.9
2.00	0.75	+229.5	−85.6	+10.7	−40.1
2.00	0.50	+241.9	−84.6	+1.10	−41.2
1.50	1.00	+195.9	−83.5	+6.60	−39.6
1.50	0.75	+221.1	−85.2	+11.1	−40.7
1.50	0.50	+228.7	−85.4	+4.80	−41.7
1.00	1.00	+191.8	−85.8	+4.10	−40.3
1.00	0.75	+226.8	−85.6	+14.2	−41.1
1.00	0.50	+208.3	−85.0	+3.30	−41.9

The minimum ultimate bearing capacity and maximum elastic settlement of each case study, which were computed from new approach, were selected as critical design values to be compared with the routine design methods. As shown in Table 5, the ultimate bearing capacity of each foundation increases by as much as 230% of the conventional method in Victorville, while this is utmost 10% for Levelland. In case of the settlement criteria, the foundation settlement of each studied case decreases by almost 85% and 40% at Victorville and Levelland, respectively. It can be concluded from this comparison that the effect of either matric suction or degree of saturation in foundation design parameters for any region depends on the inherent soil characteristics, which are affected by the depth to which water infiltrates the influence zone of the foundation.

6. SUMMARY AND CONCLUSION

The coupled geotechnical-hydrological model defined in this study was used to incorporate the climatic and subsurface data with the routine process used in shallow foundation design. This novel method evaluates ultimate bearing capacity and elastic settlement due to the matric suction and degree of saturation of the soil within the foundation influence zone. The infiltration of rainwater through initially partially saturated subsurface soil was modelled using the one-dimensional Richards' equation considering both rainfall intensity and water table location as the top and bottom boundary conditions, respectively. To calculate the bearing capacity and settlement of various shallow foundation sizes, the average degree of saturation and matric suction within the influence zone including the soil capillary were computed by applying 10,000 random input values corresponding to the rainfall and water table distributions using Monte Carlo simulation.

Two sample sites were selected in this study to show the variation of ultimate bearing capacity and elastic settlement with matric suction (or degree of saturation); Victorville, CA, and Levelland, TX. After 3 days continuous rainfall and ignoring the effect of surface runoff and evapotranspiration, the degree of saturation in Victorville was between 55% and 84%, and between 25% and 35% in Levelland. The small variation in degree of saturation at Levelland is caused by the existence of the fine-grained soil at this area which is less permeable. It is also found that considering the matric suction in a shallow foundation design increases the ultimate bearing capacity of a foundation by almost 230% of the bearing capacity calculated considering a fully saturated condition. However, the effect of the matric suction can be changed depending upon the depth of water infiltration into the soil. In terms of settlement criteria, the elastic settlement of various footing sizes has been decreased to approximately 85% and 40% of the settlement considering fully saturated condition in Victorville and Levelland, respectively. As the influence depth of the foundation increases, the matric suction range becomes narrower, thus the ultimate bearing capacity reached its higher values, whereas the elastic settlement decreased with the opposite trend. A comparison of the results determined that the common foundation design procedure overestimates the foundation design parameters in compare with the actual condition of the site locations even for extreme hydrological events.

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