Influences of rainfall infiltration and hysteresis SWCC of unsaturated soil on settlement of shallow foundations

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ABSTRACT

Influences of rainfall infiltration on the settlement of shallow foundations in unsaturated soil were numerically investigated. A computer based finite element analysis using PLAXIS 2D is used to estimate the effects of rainfall infiltration and hysteresis on the settlement behavior of the shallow foundations by incorporating the hysteretic soil-water characteristic curve (SWCC) of unsaturated soils derived from laboratory. There is a good comparison between load-settlement responses and variations in matric suction calculated from the numerical model in the present study were in good agreement with the field measurements. The results of the parametric studies highlight the rainfall intensity played a significant role in the wetting-induced settlement of shallow foundations in unsaturated soil. The wetting-induced settlement during rainfall was also affected by the groundwater table position near the ground surface due to changes in matric suction. In addition, the analysis by a wetting SWCC produced a slight larger settlement up to 5% than that of a drying SWCC. Therefore, appropriate SWCCs (i.e., drying or wetting) is encouraged in the numerical analysis in accordance with the condition that the soils underneath shallow foundations experience.

Keywords: Settlement, Shallow foundation, Unsaturated soil, Rainfall infiltration, Modulus of elasticity, Sequential analysis

1 INTRODUCTION

Shallow foundations have been built within unsaturated zones ignoring the influence of matric suction that is closely related to shear strength of soil (Rojas et al. 2007; Vanapalli and Mohamed 2007; Jeong et al. 2008; Kim et al. 2016; Wu and Selvadurai 2016). A settlement is one of the key parameters in designing shallow foundations, which might be affected by matric suction in accordance with the principles of unsaturated soil mechanics. However, the conventional design of shallow foundations has been carried out in accordance with the principles of saturated soil mechanics. A considerable number of researchers have studied the effects of matric suction on the strength of unsaturated soil. Rahardjo et al. (2011) reported that the modulus of elasticity in unsaturated soil appears to increase with increasing matric suction. Oh et al. (2009) has also formulated the variation of the modulus of elasticity with respect to matric suction as a functional relationship incorporating the soil-water characteristic curve (SWCC). Nevertheless, it can be pointed out that most studies have been neglecting the effect of matric suction, resulting in an overestimation of the settlement of shallow foundations. Despite a growing interest in the use of matric suction for assessing the settlement, very few studies have examined the transient process inducing the additional settlement of shallow foundations through laboratory or model tests. Main influencing factors on the fundamental mechanism of the settlement behavior of shallow foundations were investigated (Briaud and Gibbens 1999; Oh and Vanapalli 2011; Mohamed 2014). Numerical studies were also carried out to estimate the settlement of shallow foundations under steady-state and transient conditions (Abed and Vermeer 2009; Park 2017). However, while these previous studies were focused on the effect of matric suction, few studies have been performed on the effect of rainfall infiltration for shallow foundation stability because of the uncertainties in boundary conditions and difficulties in determining the input parameters for constitutive equations.

Unsaturated soils below the shallow foundation typically experience wetting-drying cycles due to the reasons mostly associated with climatic condition. The
wetting-drying cycles have a significant impact on SWCCs (Fredlund and Rahardjo, 1993). The hysteresis may affect the mechanical behavior and transient process in unsaturated soils (Nuth and Laloui, 2008; Rahardjo et al., 2013; Kim et al., 2016). However, the effect of hysteresis has been also ignored in assessing the settlement of shallow foundations. In particular, there was no study carried out on the investigation of hysteresis for simulations of a shallow foundation under rainfall.

This study has undertaken a two-dimensional (2D) finite element (FE) analysis using the commercial software, PLAXIS 2D (2012) to study the load-settlement response of shallow foundations in unsaturated soil under rainfall. The numerical model and analysis results were validated against experimental data. The relative importance of rainfall intensities and groundwater table positions in inducing the additional settlement of shallow foundations was investigated through a series of parametric studies. Special attention was given to the effect of hysteresis on the settlement behavior of shallow foundations by incorporating hysteretic SWCCs obtained from laboratory.

Two different groundwater table positions (1B and 2B below a ground surface, where B is the foundation width) and three assorted rainfall intensities (10, 20, and 30 mm/h) contributing to the wetting-induced settlements were used in the numerical analyses. Index properties and hysteretic SWCCs of weathered granite soil from Dogye area in Korea were incorporated into the numerical analyses. The modulus of elasticity for unsaturated soil was determined using the semi-empirical model proposed by Oh et al. (2009). The hysteretic SWCCs for unsaturated soil were measured using the apparatus by Wayllace and Lu (2012). In combination of FE results, the observation gives the insight to understand the influence of rainfall infiltration and hysteresis on the settlement behavior of shallow foundations in unsaturated soils.

2 NUMERICAL MODELING OF UNSATURATED SOIL

2.1 Modulus of elasticity

During rainfalls, unsaturated soils can become saturated and may lose all of its additional strength because negative pore-water pressure that contributes the additional shear strength increase to zero or to positive values. Therefore, it is necessary to incorporate not only the shear strength but also the modulus of elasticity of the soil in assessing the settlement of shallow foundations. Oh et al. (2009) performed model footing tests for three different sands under different matric suctions to investigate the load-settlement behavior of model footing. They developed a semi-empirical equation to estimate the modulus of elasticity for unsaturated soils with respect to matric suction using the modulus of elasticity for saturated condition, SWCC, and fitting parameters ($\alpha$ and $\beta$) as follows:

$$E_{l(sat)} = E_{l(sat)} \left[1 + \frac{(\psi - \psi_w)}{(P_a/100)}(s^{\beta})\right] \phi_{p} + 0.8 \psi_p$$

where $E_{l(sat)}$ is the modulus of elasticity under unsaturated condition, $E_{l(sat)}$ is the modulus of elasticity under the saturated condition, $P_a$ is the atmospheric pressure (i.e., 101.3 kPa), $S$ is the degree of saturation, $\alpha$ and $\beta$ are the fitting parameters. The nonlinear variation of the modulus of elasticity with respect to matric suction is dependent on $\alpha$ and $s^{\beta}$ in Equation 1. The relationship between matric suction and degree of saturation can be obtained from the SWCC. This study utilized Equation 1 with the fitting parameter values of $\alpha = 0.04$ and $\beta = 0.8$ to estimate the modulus of elasticity for unsaturated soils in the numerical analyses.

2.2 Negative pore-water pressure

Variations in negative pore-water pressure with depth can be calculated by defining an initial groundwater table position and maximum negative pore-water pressure head on the assumption that it varies hydrostatically with distance above and below the initial groundwater table as shown in Figure 1. If the maximum negative pressure head, $H_{max}$, is lower than the height of the unsaturated soil layer, $H_{unsat}$ (i.e., $H_{max} < H_{unsat}$), the negative pore-water pressure is constant up to the ground surface beyond the maximum negative pressure head. On the other hand, if the maximum negative pressure head is greater than the height of the unsaturated soil layer (i.e., $H_{max} > H_{unsat}$), the negative pore-water pressure increases hydrostatically up to the ground surface.

![Fig. 1. Modeling of pore-water pressure using PLAXIS 2D software.](image)

2.3 Cohesion and dilatancy angle

For sands, the internal frictional angle is not influenced by matric suction (Vanapalli et al. 1996; Wang et al.2002). However, Hossain and Yin (2010) reported that the dilatancy angle of unsaturated soils increases with an increase in matric suction based on their laboratory test results. Nevertheless, this cannot be used to explain the entire mechanics of dilatancy angle...
of unsaturated sand. The increasing of friction angle for unsaturated sands can be explained using the equation proposed by Bolton (1986),

\[
\phi' = \phi_{\text{crit}}' + 0.8\psi_p \tag{2}
\]

where \(\phi'\) is the effective internal friction angle, \(\phi_{\text{crit}}'\) is the critical state internal friction angle, and \(\psi_p\) is the peak dilatancy angle given by

\[
\psi_p = \begin{cases} 6.25I_R & \text{for plane strain condition} \\ 3.75I_R & \text{for triaxial conditions} \end{cases} \tag{3}
\]

where \(I_R\) is the dilatancy index that is given by

\[
I_R = I_D \left[ Q + \ln \left( \frac{P_A}{100P_0} \right) \right] - 1 \tag{4}
\]

where \(I_D\) is the relative density (as a number between 0 and 1), \(P_A\) is the reference pressure (= 100kPa), \(P_0\) is the mean effective stress at peak strength, and \(Q\) is the intrinsic soil variable, approximately equal to 10 for silica sands (Lee and Salgado 2002).

Hence, \(\phi_{\text{crit}}'\) is the friction angle of sands under the critical state (shearing occurred without any dilatancy).

\(\phi_{\text{crit}}'\) is often regarded as constant for sand under different conditions, then increasing of dilatancy angle means increasing of friction angle. Therefore, it is implemented to represent the variation of dilatancy angle with the friction angle.

3 NUMERICAL VALIDATION

3.1 Field load tests of shallow foundations

The field test program of Texas A&M University National Geotechnical Experimentation Site (Briaud and Gibbens, 1999) was chosen to investigate the response of shallow foundations subjected to vertical load in unsaturated soils. A series of field and laboratory tests were performed to characterize the in-situ soil properties.

Four sets of foundations were tested at the sand site (i.e., 1.0×1.0 m², 1.5×1.5 m², 2.5×2.5 m², and 3.0×3.0 m²).

The SPT results indicate that the soil in the upper layer at a depth of 11 m was medium dense silty sand. Fine material contents were from 2 to 8 % and 5 to 30 % at 3 m and 9 m depth, respectively. Below the sand layer overlain by hard clay layer until a depth of 33 m from ground level. According to the Unified Soil Classification System (USCS), the weathered soil was classified as silty sand (SM). Grain-size distribution curves with depth and index properties of soils based on the site investigations are summarized in Table 1.

Numerical analyses were carried out to simulate the load-settlement response of four different sizes of plate load tests for unsaturated conditions using the commercial software, PLAXIS 2D (2012). A drained condition was considered during the load-settlement simulation. The model boundaries extended to 18 m in depth and 30 m in width. The vertical boundaries were restrained in the horizontal direction, while it was free in the vertical direction. The bottom boundary was restrained in both vertical and horizontal directions.

The sand and foundation were modeled using triangular elements with 15 nodes. The sand was modeled as an elasto-plastic material using the Mohr-Coulomb model considering the dilatancy effect of the sand. The shear strength parameters (\(C'\), \(\phi'\)) and dilatancy angle (\(\psi\)) of the sands for unsaturated conditions were incorporated into the Mohr-Coulomb model. In particular, the modulus of elasticity \(E_{(\text{unsat})}\) of unsaturated soil was estimated from Equation 1 with fitting parameters (\(\alpha = 0.05\) and \(\beta = 1.0\)). The calculated \(E_{(\text{unsat})}\) was manually implemented by PLAXIS 2D (2012). The footing was modelled as a linear-elastic material. The material properties of unsaturated soils and foundation used in the numerical analysis are presented in Table 2.

Table 1. Index properties of soil at load test site (Briaud and Gibbens 1999).

| Soil Property      | Value |
|--------------------|-------|
| Specific gravity, \(G_s\) | 2.64 |
| Water content, \(w\) (%) | 5.0  |
| Void ratio, \(e\) | 0.78 |
| Unity weight, \(g\) (kN/m³) | 17.75 |
| USCS               | SM    |

Table 2. Material properties of unsaturated soil and foundation used in numerical analysis.

| Soil Property      | Value |
|--------------------|-------|
| Effective internal friction angle, \(\phi'\) (deg) | 35    |
| Effective cohesion, \(C'\) (kPa) | 1     |
| Dilatancy angle, \(\psi\) (deg) | 26    |
| Poisson’s s Ratio, \(\nu\) | 0.3  |
| Modulus of elasticity of soil, \(E_{(\text{unsat})}\) (MPa) | 45    |
| Modulus of elasticity of footing, \(E_{\text{footing}}\) (MPa) | 10,000 - 70,000 |

Distributed load was applied vertically over the footing without the eccentricity. An initial stress was developed by deactivating the foundation. It is assumed that the self-weight of the foundation was added to the distributed load. Two staged constructions were carried out. In the first staged construction, the foundation was placed and in the second staged construction, the loading was activated. Finally, an incremental multiplier was applied for the vertical load to failure. The simulations of different size of shallow foundations were performed with plane dimensions 1.0×1.0 m², 1.5×1.5 m², and 2.5×2.5 m², and 3.0×3.0 m².

Figure 2 shows the predicted and measured load-settlement responses for different size of foundations. As shown in the figure, the results of the numerical analyses were very close to those obtained from the
field load tests of 1.0×1.0 m², 1.5×1.5 m², 2.5×2.5 m², and 3.0×3.0 m² foundations. A stiffer load-settlement response was observed in the field load test of 1.5×1.5 m² foundation as compared to the result of the numerical analysis. This indicates the limitation of the numerical analysis method used in this study. The settlement behavior of shallow foundations in the unsaturated soil, which depends on types of soil, degree of saturation, anisotropy, cannot be simply simulated through the numerical method in an idealized condition. Although the numerical analysis method presented in this study has such limitations, the general trend of the measured settlement behavior of the foundations was fairly well predicted.

The cases of 3.0×3.0 m² foundation exhibited higher settlement than the relatively lower dimensions as shown in Figure 2d. However, Briaud (2007) suggested that the size effect can be eliminated by plotting the load normalized settlement (i.e., δ/B) curves. Similar trends are reported in the literatures (Palmer 1947). According to the report published by Federal Highway Administration (1997), this behavior can be explained using triaxial test analogy. If triaxial tests are conducted for identical sand samples under the same confining pressure where the top platens are different sizes of footings, the stress versus strain behaviors for the samples are unique regardless of the diameter of the samples. In addition, Consoli et al. (1998) reported that the uniqueness of the normalized curves can be observed at sites where the soils are homogeneous and isotropic in nature. Thus, the size effect can be ignored in the numerical analyses and results.

4 EFFECT OF RAINFALL INFILTRATION ON SETTLEMENT BEHAVIOR OF SHALLOW FOUNDATION

4.1 FE model and input parameters

The sequential analysis was conducted to highlight the effect of rainfall infiltration on the settlement of shallow foundations under different hydraulic boundary conditions. The settlement was assessed through the rainfall intensities, rainfall durations, and different groundwater table positions.

Figure 3 shows the initial and boundary conditions for a simple circular foundation under rainfall. A 5.0×5.0 m² foundation was resting on the unsaturated soil of 30 m height followed by 55 m of length.

Dogye weathered granite soil in Korea was selected to carry out parametric studies. The groundwater table position was assumed to be either 1 or 2 B below the ground surface, where B is the foundation width. Poulos and Davis (1974) suggested that when a load is applied to a shallow foundation, the stress transferred to the ground due to the load is predominant in the 0 to 1.5B depth region. The stress increment below a square foundation at a depth deeper than 1.5B is less than 15% of the applied stress at the ground surface.

The drying and wetting SWCCs tested from laboratory were employed as shown in Figure 4. The mechanical and hydraulic properties of the soil used in the numerical analysis are summarized in Tables 3 and 4, respectively. The influence of hysteresis between drying and wetting processes was taken into account in the analysis. Boundary conditions were applied to the foundation model for the transient seepage analysis. The flux boundary, q, equal to the desired rainfall intensity (e.g., 10 mm/h, 20 mm/h and 30 mm/h) and duration (1 h to 96 h) were applied to the top surface of the ground. The impermeable boundary condition on the right, left and bottom sides of the soil was applied to simulate no flow zones. The finite element model of the whole foundation was discretized with a mesh size of approximately 0.75m to obtain accurate results. The analysis cases with respect to rainfall intensities and groundwater table positions are summarized in Table 5.

![Fig. 2. Comparison of load-settlement responses between numerical and measured results.](image-url)
Fig. 3. 2D finite element model and boundary condition used in parametric study.

Fig. 4. Soil-water characteristic curves for Dogye weathered granite soil.

Table 3. Index properties of Dogye weathered granite soil.

| Index property       | Value       |
|----------------------|-------------|
| Specific gravity, $G_s$ | 2.72        |
| Maximum dry unit weight, $Y_{d,max}$ (kN/m$^3$) | 17.5        |
| Minimum dry unit weight, $Y_{d,min}$ (kN/m$^3$) | 13.5        |
| Coefficient of uniformity, $C_u$ | 9.27        |
| Coefficient of gradation, $C_g$ | 1.47        |
| Plastic limit, PL (%) | 12.17       |
| Plastic index, PI (%) | 16.18       |
| Saturated hydraulic conductivity, $K_s$ (m/s) | $4.76 \times 10^{-7}$ |
| USCS Classification | SW          |

Table 4. Soil-water characteristic curve fitting parameters predicted by van Genuchten (1980).

| Index property       | Drying SWCC | Wetting SWCC |
|----------------------|-------------|--------------|
| Saturated volumetric water content, $\theta_s$ | 0.418 | 0.387 |
| Residual volumetric water content, $\theta_r$ | 0.032 | 0.032 |
| Degree of saturation, $S_r$ (%) | 0.077 | 0.083 |
| Fitting parameter, $\alpha$ (1/kPa) | 0.042 | 0.643 |
| Fitting parameter, $n$ | 1.469 | 1.353 |
| Fitting parameter, $m$ | 0.319 | 0.261 |

Table 5. Summary of combination of factors affecting settlement used in parametric study.

| Soil types       | Footing size | Groundwater table position | Rainfall intensity | Rainfall duration |
|------------------|--------------|-----------------------------|--------------------|-------------------|
| Dogye weathered granite soil | 5 × 5 m$^2$ | 1B | 10 mm/h | 1hr |
|                   |              | 2B | 20 mm/h | 12hrs |
|                   |              | 2B | 30 mm/h | 23hrs |
|                   |              | 2B | 48hrs | 96hrs |

4.2 Settlement behavior during rainfall

Variations in the settlement of shallow foundations with respect to rainfall intensities (10, 20 and 30 mm/h) and groundwater table positions (1B and 2B) in Dogye weathered granite soil under the constant stress of 170 kPa are shown in Figure 5. The plots of variations in settlements versus time under different rainfall intensities show that rainfall infiltration induced the settlement increase due to the loss of matric suction above the groundwater table. As the rainfall intensity escalates, the settlement under groundwater table 2B below increased gradually and the rate of additional settlement tended to be influenced by the rainfall intensity. On the contrary, the settlement under groundwater table 1B below increased rapidly and the rate of additional settlement was significant as compared to those of groundwater table 1B below. This could be attributed to initial matric suction that governs infiltration rate of the soil. The modulus of elasticity of unsaturated soils with respect to different matric suction distributions was incorporated in the numerical analysis. It is also observed that the groundwater table near the top surface of soil yielded the additional settlement as compared to the deeper groundwater table.

Fig. 5. Variations in the settlement of shallow foundation under 170 kPa applied stress in Dogye weathered granite soil with the drying SWCC.
4.2 Effect of hysteresis during rainfall

The soil below the foundations typically experiences wetting-drying cycles due to the reasons associated with climatic condition (i.e., rain infiltration or evaporation). Hence, it is also important to estimate the variation of load-settlement behavior under hysteretic conditions. The general trend of the settlement was similar to the results of the drying SWCC. However, the amount of settlements slightly increased up to 5% as compared to those of the drying SWCC. The settlement should be affected by the modulus of elasticity with respect to matric suction. At same volumetric water content, the wetting SWCC exhibited lower matric suction as compared to those of the drying SWCC. Consequently, the relatively smaller modulus of elasticity was considered in the analysis when the wetting SWCC was employed as shown in Figure 6. Similar results concerning the effect of hysteresis on infiltration and shear strength in unsaturated soils were found by Goh et al. (2013) in their experimental study. They concluded that the sand-kaolin specimens on the drying paths have higher shear strengths than those on the wetting paths.

The settlements of shallow foundations obtained from numerical analyses with various hydraulic conditions are summarized in Table 6.

![Figure 6: Variation of modulus of elasticity with respect to matric suction for Dogye weathered granite soil.](image)

Fig. 6. Variation of modulus of elasticity with respect to matric suction for Dogye weathered granite soil.

| Time | Groundwater table 2B below (mm) | 0 | 29.02 | 30.05 | 30.05 | 29.00 | 30.00 | 30.23 |
|------|-------------------------------|----|-------|-------|-------|-------|-------|-------|
| 6    | 29.33                         | 31.90 | 31.03 | 29.13 | 31.89 | 32.00 |
| 12   | 30.02                         | 34.63 | 33.50 | 30.00 | 34.11 | 34.85 |
| 24   | 31.22                         | 35.89 | 34.28 | 31.86 | 37.46 | 37.91 |
| 36   | 32.95                         | 38.81 | 38.95 | 33.62 | 40.01 | 42.02 |
| 48   | 38.17                         | 41.71 | 43.74 | 38.95 | 43.54 | 46.25 |
| 96   | 51.53                         | 58.02 | 77.26 | 52.55 | 60.33 | 76.57 |

Table 6. Summary of settlements for shallow foundation with various hydraulic conditions.

| Time | Soil with drying SWCC 10mm/h 20mm/h 30mm/h | Soil with wetting SWCC 10mm/h 20mm/h 30mm/h |
|------|-------------------------------------------|------------------------------------------|
| 0    | 46.98 46.31 46.13 | 46.99 46.45 46.81 |
| 6    | 47.25 48.22 48.52 | 47.28 48.09 48.46 |
| 12   | 47.04 48.40 48.90 | 48.11 50.00 51.55 |
| 24   | 49.05 52.84 53.94 | 50.00 55.26 58.31 |
| 36   | 54.84 63.36 64.17 | 56.62 66.49 69.94 |

5 CONCLUSIONS

The main objective of this study is to numerically investigate the settlement behavior of shallow foundations subjected to rainfall infiltration. For this work, the sequential finite element modeling has been presented and discussed by taking into account the modulus of elasticity of unsaturated soils and the hysteresis of soil-water characteristic curves. The simulation techniques and analysis results were favorably validated in the experimental data in terms of load-settlement curves on the various size of foundations and variations in field matric suction.

In addition, to examine the influencing factor of the settlement behavior, a series of parametric studies were performed. Based on the finding of this study, the following conclusions can be drawn:

1. By taking into account the influence of matric suction in unsaturated soils, numerical results of load settlement responses for four different sizes of shallow foundations and variations in matric suction were in good agreement with the field measurements. The initial matric suction of unsaturated soils showed obvious strengthening effects for bearing capacity of shallow foundations with decreasing the settlement due to the high modulus of elasticity as matric suction increases.

2. The rainfall intensity played a significant role in determining the settlement of shallow foundations in unsaturated soils. It can be said that the wetting-induced settlement was mainly caused by rainfall infiltration and loss of matric suction. In addition, changes in the settlement during rainfall were significantly affected by the groundwater table position near the ground surface due to changes in initial matric suction.

3. The analysis by the wetting SWCC produced a slightly larger settlement of the shallow foundation up to 5% than that of the drying SWCC. For rigorous analysis and design, therefore, the appropriate SWCCs (i.e., drying or wetting) should be employed in accordance with the condition that the soils underneath shallow foundation experience.
Based on the results presented in the paper, a framework for modeling of unsaturated soil in sequential numerical analyses provides a good understanding of the mechanism leading to wetting-induced instability of shallow foundations under the transient condition that leads to an additional settlement.

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