

COUPLED AND UNCOUPLED APPROACHES FOR THE ESTIMATION OF 1-D HEAVE IN EXPANSIVE SOILS DUE TO TRANSIENT RAINFALL INFILTRATION: A CASE STUDY IN CENTRAL VIETNAM

*The Viet Tran¹, Minh Thu Trinh²

¹Faculty of Civil Engineering, Thuyloi University, 175 Tay Son, Dong Da, Hanoi, Vietnam

² Faculty of Civil Engineering, Thuyloi University, 175 Tay Son, Dong Da, Hanoi, Vietnam

*Corresponding Author, Received: 25 July 2019, Revised: 20 Sept. 2019, Accepted: 26 Oct. 2019

ABSTRACT: In this study, we utilized the coupled and uncoupled approaches in Geostudio commercial program to simulate the swelling of expansive soil caused by rainfall infiltration. For the coupled analysis in general, the infiltration of rainfall and subsequent heave are modeled using fully coupled formulation in SIGMA/W; specifically, the displacements and pore-water pressure changes are computed simultaneously. In the uncoupled analysis, rainfall-induced pore-water pressure change was simulated using SEEP/W alone and the resulting pore-water pressure change was employed in SIGMA/W for the volume change analysis. In other words, to analyze the problem in an uncoupled manner, the pore-water pressure changes and volume changes are computed separately. For the above purpose, the residual soil in Bac Ai district, Ninh Thuan province, South Central Vietnam, a well-known place with expansive soil problems was considered. The result shows that both proposed methods are promising tools and can be used in engineering practice for the estimation of the 1-D heave due to rainfall infiltration with respect to time.

Keywords: Coupled analysis, Uncoupled analysis, Expansive soil, Volumetric change, Rainfall Infiltration

1. INTRODUCTION

Expansive or swelling soils are considered to be problematic soils in the literature, they can be found on nearly all continents. The engineering properties of such types of soils are highly sensitive to changes in water content and suction in the active zone depth [1]. The destructive effects caused by swelling soil have been reported in many countries around the world [2, 3, 4]. As the loss due to the damage of structures caused by swelling soils is expected to increase, it is practical significance to improve the knowledge and understanding of the fundamental behavior of expansive soils subjected to water infiltration as well as the methodology for civil engineering structures those constructed on such type of soils [2, 5].

Swelling pressures associated with changes in water content and suction of unsaturated expansive soils are responsible for the undesirable heave movements contributing to considerable damages to the above structures [1]. Therefore, neglecting the swelling-induced stress changes behavior can largely overestimate the stability of expansive soil at shallow depth under infiltration [3]. The response of a swelling soil foundation subjected to rainfall infiltration may be very different from that of conventional non-swelling soils. The damage of

expansive soils is closely associated with the strong soil-water interaction in the shallow layers subjected to seasonal wetting-drying cycles [4]. According to Rao et al. (2014) [6], in conventional engineering practice, expansive soils swell during the wet season by absorbing water and the volume change of such soil may result in severe distress on light structures founded on them. Therefore, evaluation of swelling characteristics of expansive soils, including, swelling potential and swelling pressure, has a great meaning in the design of foundations [6].

The heave behavior of expansive soils in the field is complex as it is influenced by numerous factors including various soil properties as well as environmental conditions [7]. Reliable determination or estimation of the swelling pressure and the soil heave, however, has been proven to be difficult to date [1]. Soil expansion can be attributed to the existence of highly active clay minerals that contribute to large volume change upon wetting in expansive soils [8]. Based on laboratory tests, Zhan et al. (2007) [4] concluded that the soil-water interaction induced by the climatic changes is very complicated involving the coupled effects among changes in water content, suction, stress, deformation, and shear strength. The stress-deformation process is governed by static

equilibrium, while the water flow is controlled by the static equation. Solutions for volume change require that both the equilibrium equation and the continuity equation be solved [9].

Fully coupled formulations for the swelling theory of unsaturated soils were initially introduced in the 1980s [10]. Based on this theory, the fully coupled analysis requires both the stress-deformation and seepage equations to be solved simultaneously or the transient interdependence between the seepage and deformation problems is fully realized [9]. However, in several cases, to avoid the problems of numerical instabilities and to save the computation time, instead of solving the two sets of equations simultaneously, it is numerically beneficial to solve the transient flow equations in advance. The related volume change is then computed for the previously simulated pore pressure changes. This is known as an uncoupled analysis [11]. Uncoupled solutions can be more easily achieved than that of coupled solutions because the soil property functions involved in each process are considered to be independent of one another [9, 11]. In general, the coupled analysis provides a more rigorous understanding of the swelling behavior of expansive soils and forms a reference for the evaluation of various uncoupled analyses [5].

One of the major geotechnical problems associated with construction in expansive soils is to estimate the variation of heave over time [7]. The 1-D heave of expansive soils is typically estimated based on the results of either oedometer swelling tests or suction tests. However, the procedures related to these tests are tedious and time-consuming. Besides, the swelling pressure measured from oedometer swelling tests may result in the overestimation of ground heave since the soil specimen is submerged until the specimen attains a fully saturated condition [13].

This study applied the coupled and uncoupled approaches to simulate the swelling rate of expansive soils caused by rainfall infiltration over time. SIGMA/W alone was used in the coupled approach. SEEP/W and SIGMA/W were combined to simulate the uncoupling stress-strain and seepage analysis in the uncoupled approach. For the purpose of comparison, a parallel coupled (SIGMA/W alone) and uncoupled analysis (SEEP/W and SIGMA/W) in Geostudio software were conducted to simulate the 1-D heave of a typical expansive soil in central Vietnam subjected to a low-intensity prolonged rainfall. The expansive residual soil in Bac Ai district, Ninh Thuan province, South Central Vietnam is considered.

2. THEORETICAL LINK BETWEEN RAINFALL INFILTRATION AND THE RESPONSE OF EXPANSIVE SOIL

Swelling soil deforms in response to the changes in the stress condition caused by the transient infiltration. Therefore, it is clearly a time-dependent process involving nonlinear soil properties [9]. The response of unsaturated expansive soil to water infiltration is a highly coupled hydro-mechanical process, including water flow through the unsaturated porous medium and stress change induced by soil swelling [8]. The engineering behavior of expansive soils is sensitive to both the changes in water content and as well as the variation of matric suction [1].

According to Adem (2015) [5], the volume change behavior of expansive soils can be explained by the mechanisms of unsaturated soils through the use of the constitutive relationships that related to the deformation state and the stress state variables. Unlike in the saturated medium, the behavior of unsaturated expansive soil is formulated using two independent stress state variables including the net normal stress ($\sigma - u_a$) and matric suction ($u_a - u_w$) [9]. In SEEP/W, the saturated and unsaturated transient flow through a porous medium is characterized by the water continuity equation or Richards' equation:

$$\frac{\partial \theta_w}{\partial t} = \nabla \left[k_{unsat} \nabla \left(\frac{u_w}{\gamma_w g} + y \right) \right] \quad (1)$$

where t – is time; u_w – is the value of pore water pressure (PWP), γ_w – is the density of water; g – is the gravitational acceleration; y – the elevation; θ_w – is the volumetric water content; k_{unsat} – is the permeability of soils under unsaturated condition; ∇ – is the gradient operator.

In Eq. (1), both θ_w and k_{unsat} are linked to the PWP (u_w) with nonlinear functions [8]. The equation shows the difference between the flow in and out of an elemental volume and the rate of variation of the volumetric water content with respect to time [14]. The gradient operator ∇ is characterized as

$$\nabla = \frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} k \quad (2)$$

The stress field within an unsaturated medium is defined using the partial differential equations of static equilibrium as follows

$$\nabla(\sigma) + b = 0 \quad (3)$$

where, σ represents for components of the net total stress tensor, b represents the body force vector.

Coupling Eq. (1) and Eq. (2) gives a relatively comprehensive description of the coupled hydro-mechanical response of unsaturated soil to water infiltration [8]. The two equations can be solved either by using the coupled or uncoupled approach utilizing the numerical method. Their solutions describe the seepage and stress fields for a specific boundary condition. In literature, the commercial

finite element-based programs SEEP/W and SIGMA/W are formulated to solve soil consolidation problems using a fully coupled or any of several uncoupled options [12].

3. COUPLED AND UNCOUPLED APPROACHES FOR THE PREDICTION OF HEAVE IN SOIL SUBJECTED TO RAINFALL INFILTRATION

The primary interactive processes involved with a volume change analysis of an unsaturated expansive soil are stress deformation and water flow [9]. In this study, the swelling of a typical expansive foundation to rainfall infiltration with respect to time is modeled using the coupled and uncoupled approaches in Geostudio. The capability of SIGMA/W to conduct coupled saturated and unsaturated hydro-mechanical analysis has been verified by Wong et al. (1998) [10].

One dimensional (1D) heave was considered in this study as it is more commonly used in the estimation, prediction, and measurement in engineering practice applications [1]. For the purpose of this study, a 5.0 m height soil column which represents the general thickness of the residual soil layer in the study area was considered. The diameter of this column is 0.5 m. The initial suction value for the whole slope profile is set to be 400 kPa following the suggestion of Vu and Fredlund (2006) [9] for fairly dried regions with depth groundwater table. An infiltration flux rate caused by rainfall is then specified on the surface of the soil column.

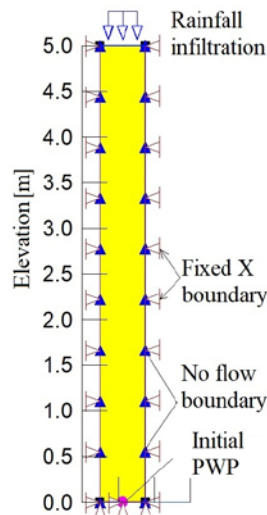


Fig.1 Boundary conditions used in a) the coupled analysis in SIGMA/W and b) in the uncoupled analysis combining SEEP/W and SIGMA/W

It should be noted that the maximum amount of rainwater that can infiltrate into the soil is limited to

the saturated hydraulic conductivity of the soils [15]. In this study, a daily flux boundary ($I = 5.7 \times 10^{-6}$ m/s) that is slightly greater than the saturated hydraulic conductivity ($K_{sat} = 5.7 \times 10^{-7}$ m/s) of the surface layer is applied to the surface of the model. The duration of the considered rainfall is 108 hours (4.5 days) which is a common long rainfall duration in the study area. The models and all the types of boundary conditions used in both the coupled and uncoupled analyses are presented in Fig. 1.

4. SOIL PROPERTIES REQUIRED FOR VOLUME CHANGE PREDICTION IN EXPANSIVE SOIL

Soil properties required for a volume change analysis include: 1) Poisson's ratio, μ ; 2) an elasticity parameter (i.e., elasticity function) for the soil structure with respect to net normal stress, E ; 3) an elasticity parameter (i.e., elasticity function) for the soil structure with respect to matric suction ($u_a - u_w$), H (the soil modulus); 4) an elasticity "type" parameter for the water phase with respect to net normal stress, E_w ; 5) an elasticity "type" parameter for the water phase with respect to matric suction, H_w ; and 6) the hydraulic conductivity function, k_w . In Geostudio, the soil modulus can be defined as follow:

$$H = \frac{6.908(1 + e_o)}{C_m} (u_a - u_w) \quad (4)$$

where C_m is the compressive index with respect to matric suction; e_o is the initial void ratio.

Table 1 Soil parameters for stress-strain analysis

Parameters	Unit	Range	Selected value
Unit weight	kN/m ³	17.6 ÷ 18.5	18
Void ratio		0.8 ÷ 1.1	1.0
Poisson's ratio		0.28 ÷ 0.32	0.3
Saturated elastic modulus	kN/m ²	3000 ÷ 3500	3000
Saturated hydraulic conductivity	m/s	$5.0 \times 10^{-7} \div 6 \times 10^{-7}$	5.7×10^{-7}

The properties of swelling soil used in this study are identical to the residual soil in Bac Ai district, Ninh Thuan province, Central Vietnam. The soil was originated from siltstones containing the montmorillonite clay mineral that is able to absorb a great amount of water. It can be classified as CL (lean clay with sand) according to the USCS. All the

utilized soil properties for simulation were taken from the laboratory tests, the results were illustrated in Table 1. To evaluate the behavior of unsaturated soil, the soil-water characteristic curve (SWCC) was constructed using the pressure plate following the ASRM D6836-12 (2003) [16]. The result is presented in Fig. 2.

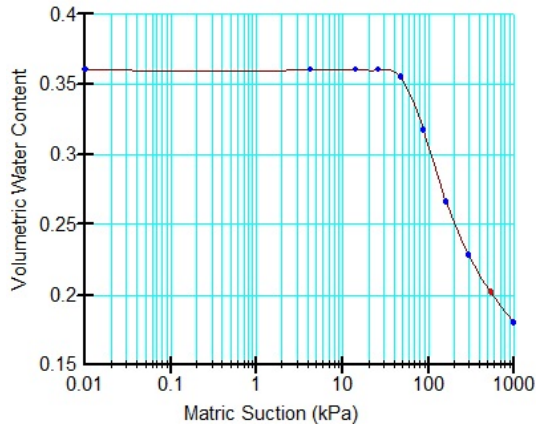


Fig.2 Soil water characteristic curve of the soil.

The soil stiffness modulus E defines the variation in Young's Modulus by mean of a function of Y -total stress as a function of the Y -coordinate, is often proportional to the square root of the confining stress [12]:

$$E = K\sigma^n \quad (5)$$

where K is a soil property and n is an exponent.

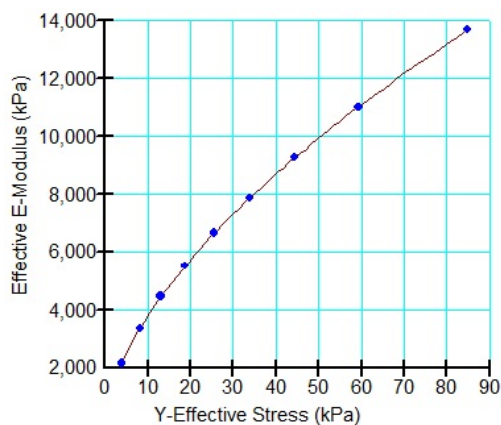


Fig 3. E-modulus function

In SIGMA/W, to estimate the E -modulus function, it is mandatory to specify a maximum depth, a K -modulus number, and exponent n and K_o value. The value of K_o and n were defined by default depending on the type of soil (in this case it is clayey sand). Their values were suggested by Duncan et al. (1980) [17] based on an extensive laboratory testing program. From the specified

values, SIGMA/W considers the nonlinear relationship between the modulus of elasticity parameters and suction as a semi-empirical model as presented in Fig. 3.

5. RESULTS AND ANALYSES

To assess the performance of the two approaches, we compare the amount of water leaving the bottom boundary (the outflow water) of the soil column over time, the change of the PWP and the resulting heave simulated by the two approaches. It is evident that the balance between the flow in and out of the soil column decides the change of the PWP condition within the model. Therefore, it is important to assess this quantity.

Fig. 4 shows the water leaving the domain via the bottom boundary over time simulated by both the coupled and uncoupled approach. As can be seen, the cumulative water volume begins to increase after 40 hours (in the coupled analysis) and 48 hours (in the uncoupled analysis), as the soil column starts to reach the steady-state condition. The outflow value at the bottom boundary in the uncoupled analysis is higher in most of the time steps meaning the required time to reach the steady-state condition in the case of the coupled analysis is shorter. Basically, a larger amount of flow out water results in smaller PWP and less heave. This trend is proved in the simulated results 48 hours after the start of the rain as presented in Fig. 5.

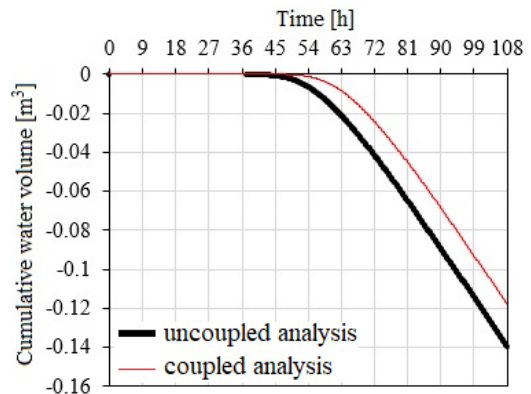


Fig.4 Water leaving the domain via the bottom boundary

Fig. 5 shows the pore pressure head and vertical displacement (Y – displacement) contours along the soil column of the coupled and uncoupled approaches 48 hours after the start of the rain. As can be seen, in this specific time step, in general, the deeper the elevation, the larger the swelling rate of the soil. Due to the infiltration of the rainwater, the suctions tend to reduce and heave increases as

indicated by the direction of the vectors. It is evident that there are some differences in the results simulated by the two approaches. The suctions have not lessened as much in the SEEP/W only analysis comparing to the fully coupled analysis. The coupled analysis shows a slightly higher pore pressure head which results in the more heave.

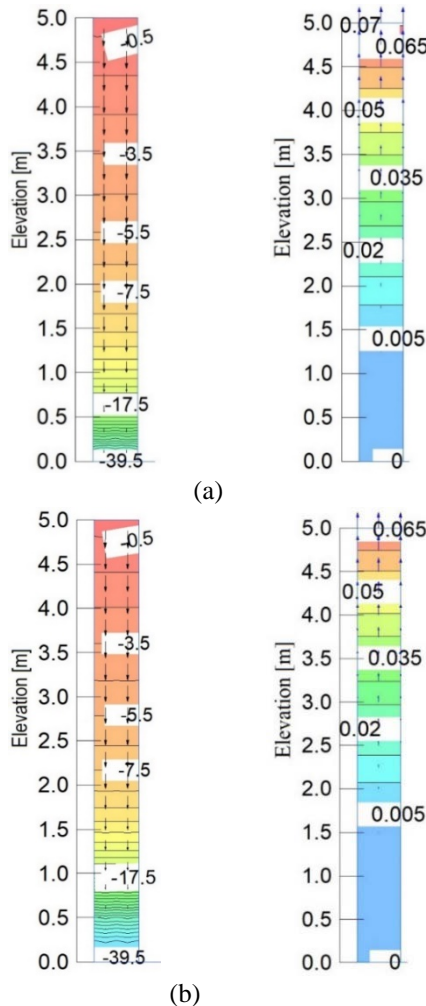


Fig.5 *PWP* head [kPa] and displacement contours [m] simulated 48 hours after the start of the infiltration simulated by a) the coupled and b) uncoupled approaches, the direction of the vectors showing the seepage and swelling direction of the soil mass.

It is clear that the processes of rainfall infiltration cause the moisture content to increase, the matric suction to decrease, and the soil mass to swell is time-dependent. Fig. 6 show the variation of *PWP* head along the soil column at initial condition, 2 hours, 6 hours, 12 hours, 24 hours, 48 hours, and 108 hours after the start of the infiltration. As can be seen in this figure, the *PWP* head in both cases increases rapidly at the region on or near the surface of the soil column during the infiltration

process. The deeper the elevation, the less influence of the rainfall infiltration. The matric suction at or near the surface almost equal to zero (the soil is at or near the saturated state) after about 24 hours of continuous rain. Moreover, it is evident that the pore pressure head results obtained from the coupled analyses are quite different from those obtained by uncoupled analysis at the same elapsed time. The advancement rate of the wetting front in the coupled analysis is faster in comparison to uncoupled analysis. In other words, suction loss occurs at a faster rate near the ground surface in the coupled analysis. The coupled analysis produces a sharper transition in the upper wetted zone and those at the initial condition than the uncoupled analysis. For uncoupled analysis, it takes more time for the upper zone of the surficial layer to be wetted.

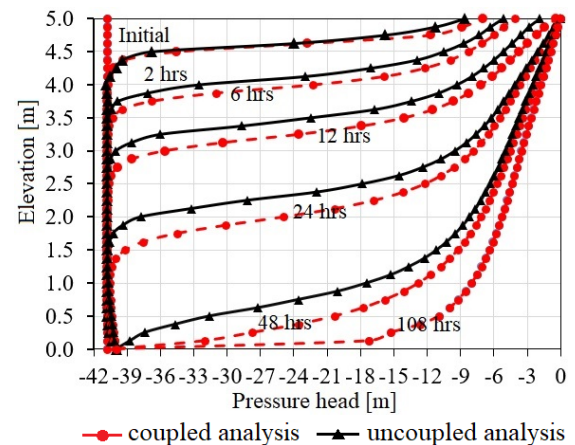


Fig.6 Vertical displacement along the soil column at different time steps

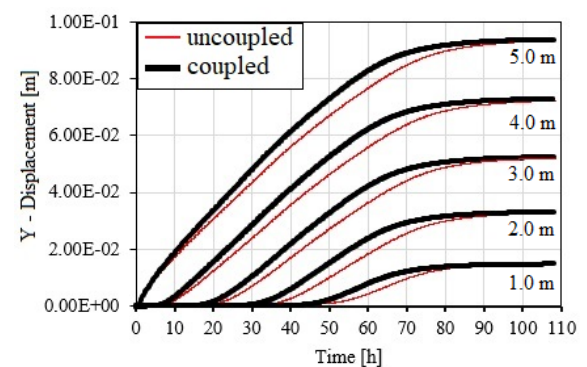


Fig. 7 Variations of heave versus elapsed time at different depths

Fig. 7 shows the variation of heave versus elapsed time with depths within the soil column during the rain. As can be seen, at all depths, the rate of increase in soil heave reduced with elapsed time. The speed of swelling fall quite considerably during the first 80 hours of rainfall. At 108 hours after the

rain starts, the ground surface reaches the maximum swelling of about 0.1 m. In addition, the heave from the uncoupled analysis is slightly less than from the coupled analysis at early times, but the results are more similar after 90 hours.

6. CONCLUSION

The study utilized the coupled and uncoupled approaches in Geostudio commercial program to simulate the 1-D swelling of expansive soil caused by rainfall infiltration. It can be concluded that changes in the stress and deformation associated with rainfall infiltration analysis in the swelling soils should be considered in engineering practice. In addition, for uncoupled analysis, it takes more time for the upper zone of the surficial layer to be wetted. The heave from the uncoupled analysis is slightly less than that of the coupled analysis at early times, but the results are more similar after 90 hours. The difference in the simulated results of the two approaches may be as a result of the fact that the advancement rate of the wetting front in the coupled analysis is faster in comparison to uncoupled analysis. Base on the advantages and disadvantages of both approaches, it is suggested that the uncoupled and coupled models should be verified against measured data and field case histories. For future studies, it is important to consider the influence of the initial matric suction conditions, and the presence of cracks and fissures on the surface of the foundation.

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